Modeling Optimal Retransmission Timeout Interval for Bundle Protocol

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Delay/disruption tolerant networking (DTN) was proposed as a networking architecture for reliable data delivery despite an extremely long propagation delay and frequent/lengthy link disruptions. The challenging problem of mission control and data delivery in deep-space explorations is a typical application scenario of the DTN technology. Reliable data delivery of DTN relies heavily on its core bundle protocol (BP). Performance evaluation and improvement of BP for deep-space communications are presently underway. The setting of the retransmission time-out (RTO) timer of BP is critical for reliable and highly efficient file transfer in a deep-space communication environment. In this paper, we present analytical modeling of an optimal RTO timer interval for the best goodput performance of BP in deep-space communications characterized by a very long signal propagation delay and lossy data links. A model is developed to compute the RTO timer interval that will result in the best goodput performance of BP normalized with respect to the total data load transmitted in order to achieve successful delivery of an entire file. Experimental validation using a PC-based testbed indicates that the RTO timer interval indicated by the model achieves the best normalized goodput performance of BP. The model predicts performance in all the experimented scenarios.

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I. INTRODUCTION

A. Research Background

Delay/disruption tolerant networking (DTN) [1] was proposed as an internetworking architecture for reliable data delivery despite a very long propagation delay and/or lengthy link disruptions. The challenging problem of mission control and data delivery in deep-space communications is a typical application scenario of the DTN technology. Deep-space communications are characterized by an extremely long signal propagation delay, random and lengthy link disruptions, lossy data links, and asymmetric channel rates. DTN is presently recognized as the only candidate protocol that approaches the level of maturity required to handle the inevitable long delays and unpredictable link disconnections inherent in deep-space communications [2]. Reliable and highly efficient data delivery of DTN relies heavily on the bundle protocol (BP) [3]. BP establishes an overlay network that is able to withstand intermittent data link connectivity in the delivery of DTN data units, termed *bundles*.

The intermittent link connectivity experienced during data delivery over a deep-space channel could be due to a link outage and/or an extremely long signal propagation delay. Link outages or disruptions in deep space occur either periodically or randomly due to such factors as spacecraft movement and/or limited relay transit duration. Mars missions are an example [4]: Mars periodically "turns its back" to earth, taking the rover on its surface 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 for most of the time of data delivery. In addition, lengthy signal propagation delays are inevitable in deep-space communications due to the long physical distance in deep space between the data source and data destination, together with the limit on the speed of light.

For an end-to-end acknowledgement (ACK) based reliable data-delivery protocol, the setting of a retransmission time-out (RTO) timer is an important factor in transmission efficiency and performance. For most protocols, the RTO timer is set based on round-trip time (RTT) estimates derived from historical RTT measurements. When the RTO timer expires prior to the receipt of the ACK, the data sender considers the corresponding data packet lost and retransmits it. If the RTO timer is set too long, it can lead to a long idle waiting time before the sender reacts to the presumably lost packet. On the other hand, if it is set to be too aggressive (i.e., too short), it might expire too often, which leads to unnecessary and frequent retransmissions. In other words, setting the RTO timer interval to an inappropriate value can have a negative impact on the efficiency and the performance of a reliable data protocol. Therefore, the key is to find a good compromise of the RTO timer interval that balances avoiding unnecessary RTO due to premature retransmission, with delayed delivery due to tardy retransmission.

The setting of the RTO timer is even more important and challenging for reliable data delivery of a protocol for deep-space communication in which the channel latency significantly varies. The situation is worsened by the frequent and random data losses resulting from strong deep-space channel noise and asymmetric channel rates. NASA has already deployed DTN's BP for disruption-tolerant data delivery from the international space station to an earth ground station [5]. Given the current status of applications and the pace of standardization progress [3], [6]–[8], BP is more likely to be deployed in future deep-space missions than any other space networking protocols. However, little work has been done in studying how to achieve the best performance of DTN's BP in deep-space communications with respect to its RTO timer setting. In this paper, we present a study of the RTO timer setting for the use of BP for file transmission over a relay-based deep-space communication infrastructure characterized by an extremely long latency, lossy data links, and asymmetric channel rates.

B. Contributions and Novelty

In this paper, for the first time, analytical modeling is presented for an optimal RTO timer interval resulting in the best goodput performance of BP in deep-space communications. A model is developed to compute the RTO timer interval that will result in the best normalized goodput performance of BP, and it is validated by file-transfer experiments. It is found that unlike the default RTO setting of TCP as commonly adopted for the terrestrial Internet, for which the RTO timer is set equal to or longer than the RTT, the optimal RTO timer interval of BP varies depending on the transmission conditions—it may be half of RTT or even shorter for its best goodput performance under communication conditions that are typical of deep-space environment. The model predicts the goodput performance of BP normalized with respect to the total amount of data transmitted in order to achieve successful delivery of an entire file, for all the file transmission scenarios studied in this paper. This paper provides a theoretical analysis of the RTO timer setting together with experimental results confirming that the model predicts the best normalized goodput performance of DTN protocol. It should be useful in designing networking protocols adopted for deep-space flight missions.

In Section II, we provide a review of the literature related to this paper. An overview of BP operation focusing, in particular, on data bundle transmission and the RTO timer setting, is presented in Section III. In Section IV, an analytical model is built for the transmission performance of BP with respect to RTO timer intervals. The results of optimal RTO timer calculation using this model are presented for different transmission scenarios in Section V. Results based on file transfer experiments are presented in Section VI, and they are also presented to validate the analytical model built in Section III. Conclusions are drawn in Section VII.

II. RELATED WORK

A significant amount of effort has been done in developing networking architectures and protocols (including DTN) for satellite communications, space networks, deep-space communications, and similar scenarios. Some of them focus on the development of network architectures and protocols for general satellite communications [9]–[11] and study of system architectures for interplanetary internet [12], [13]. Some studies focus on data transport for DTN targeting its application in space, and a comprehensive overview of them is presented in [14].

Some work [15] has been done in protocol development and performance analysis for satellite packet communications. However, they are generally not applicable to deep-space communications. The CCSDS file delivery protocol (CFDP) is developed for file transfer in deep-space scenarios. In [16], a theoretical analysis of CFDP in an immediate NAK mode is presented. Unlike our paper, the analysis in [16] is not validated by file delivery experiments based on an experimental infrastructure. A series of deep impact network experiments [17] performed by the jet propulsion laboratory (JPL) proved the feasibility of exercising DTN protocols in the deep-space environment. However, this series of work focuses on an experimental investigation of the use of DTN for space but without a solid theoretical analysis.

Wang *et al*. have conducted a series of studies [18], [19] in space networking protocol development and evaluation for their application to earth-orbit and cislunar communications. In [18], an experimental, comparative analysis of the window-based transmission control, rate-based transmission control, and a hybrid of the two over error-prone geostationary-earth orbit-space communication links is presented. In [19], the team presented an experimental investigation of the core file-delivery operation of unreliable CFDP, operating with reliable transmission control protocol (TCP), over a simulated cislunar communication link under various channel conditions.

Recently, Wang's team also did some work on DTN protocols, mainly on TCP- and the Licklider transmission protocol (LTP) based convergence layers (LTPCLs), in space communications [20]–[23]. In [20], the team presented an experimental evaluation of the DTN architecture over a simulated cislunar communication channel with a focus on the LTP convergence layer on top of UDP/IP (i.e., BP/LTPCL/UDP/IP). A method for integrating Reed-Solomon codes to LTP for use in space DTN, is presented in [21]. In [22], the team studied the effect of data bundles aggregation at LTP layer in space communications characterized by asymmetric channel rates and investigated how to achieve the best performance through data bundles aggregation. In [23], analytical models are presented to characterize LTPCL in cislunar communications for which the minimum number of bundles that should be aggregated to avoid delay in ACK transmission and the optimal number of bundles to be aggregated for the best transmission efficiency of BP/LTPCL are formulated.

The aforementioned work on DTN protocols [19]–[23] done by Wang's team target cislunar communications. Because the propagation delays of cislunar communications are orders of magnitude shorter than the propagation delays in deep-space communications, the findings from these studies may not be applicable to deep-space scenarios. In addition, most of these studies focus on experimental evaluation without the solid support of theoretical analysis. Wang's team also did some studies on performance analysis of DTN protocols in deep space [24]–[26]. In [24], the team proposed to set the RTO timer of DTN protocol shorter than the RTT and presented preliminary experimental results of tuning the RTO timer toward the highest data delivery performance. The study in [25] focuses on the analysis of the memory dynamics characterizing the use of LTP for file transmissions over a typical relay-based deep-space communication infrastructure without considering the effect of link disruptions. The study presented in [26] focuses on the transmission performance of BP in deep-space communications in the presence of lengthy link disruptions. However, none of the studies in [24]–[26] is able to develop a model which gives an accurate interval of the optimal RTO timer resulting in the best goodput performance of DTN protocol (for either BP or LTP), which we targeted in this paper.

In [27], Bezirgiannidis *et al*. presented a useful method of estimating data bundle delivery time in space internetworking using the contact graph routing computation algorithm. Similar to the work [20]–[22] done by Wang, the analysis and experimental verification in [27] are done for space communication scenarios with quite short signal propagation delay (up to 100 s); their research findings are not directly applicable to the very deep space communications that we target.

In summary, although extensive work has been done in developing network architectures and protocols for space networks and deep space communications, there is no solid analytical work done in computing the optimal RTO timer interval that will result in the best transmission performance of BP over a deep-space channel.

III. OVERVIEW OF BP AND TRANSMISSION WITH RESPECT TO RTO TIMER SETTING

As introduced, DTN communications rely heavily on BP for transmission reliability and internetworking interoperation. BP is developed to have the ability to withstand intermittent data link connectivity and the ability to make use of both scheduled connectivity and opportunistic contact for data delivery [3]. It adopts a store-and-forward mechanism and a custody transfer option for transmission reliability. In other words, BP performs custody-based retransmission of data bundles. BP allows interoperation between highly heterogeneous networks as IP does so that a store-and-forward overlay network can be formed. For a general networking architecture and protocol stack that implements such an interoperation, refer to [28, Fig. 1]. From this architecture, it is obvious that BP provides reliable data delivery hop-by-hop across heterogeneous networks in DTN, ultimately resulting in reliable delivery of bundles to the final destination.

As illustrated in the architecture in [28], a "convergence layer adapter" (CLA), residing immediately under the BP layer, is needed for a DTN node to send and receive its bundles on behalf of BP [3]. It enables BP to interact with an interfacing network within which the node is functionally located so that BP is able to use the services of that "native" network protocol to which the specific CLA functionally interfaces. Therefore, BP uses different CLAs depending on different low-layer network protocol suites deployed for each local network. For a detailed description of BP and its operational procedures, refer to [3] and [7].

The TCP-based CLA (or simply TCPCL) [29], user datagram protocol (UDP) based CLA (or simply, UDPCL) [30], and LTP [31, 32] CLA (or simply LTPCL [33]) are the broadly supported CLAs under BP. UDPCL is mainly designed to work with BP for use over dedicated private links. UDP uses a simple transmission model that provides no transmission reliability. However, if UDP works with BP (via its CLA), which enables store-and-forward services and custody transfer (i.e., under the architecture of BP/UDPCL/UDP), each DTN node keeps a copy of every bundle sent until receiving a custody acknowledgment (CA) message. The CA message confirms the successful reception of the bundle by the next node in the end-to-end path.

Unlike the operation of the TCP/IP-based Internet for which the volatile RAM memory is used for short-time buffer of data packets, BP bundles are stored in nonvolatile memory for permanent storage for delay/disruption tolerance. Their difference implies that while an IP-based router on the terrestrial Internet can discard packets immediately upon transmission, the "custodial" bundles can only be discarded when either their custody has been accepted by other DTN nodes or their application-specified life times have expired. Either bundles or acknowledgements may be lost or corrupted over a lossy deep-space channel. Transmission, acknowledgment, and possible retransmission of data bundles are handled individually for each bundle. A custodial bundle may be retransmitted in order to recover from data corruption on a lossy channel, but the node that has taken custody of the bundle and has transmitted it will not retransmit the data until the bundle's RTO timer expires prior to reception of the corresponding acknowledgement.

As discussed, the setting of the RTO timer is critical for reliable data delivery of a protocol for deep-space communications. In comparison to the terrestrial Internet channels, deep-space channels are characterized by an extremely long and varying RTT accompanied by high data/ACK loss. A high rate of data loss causes frequent expirations of the RTO timer. Because the timer determines when the lost bundles should be retransmitted, the configured RTO timer

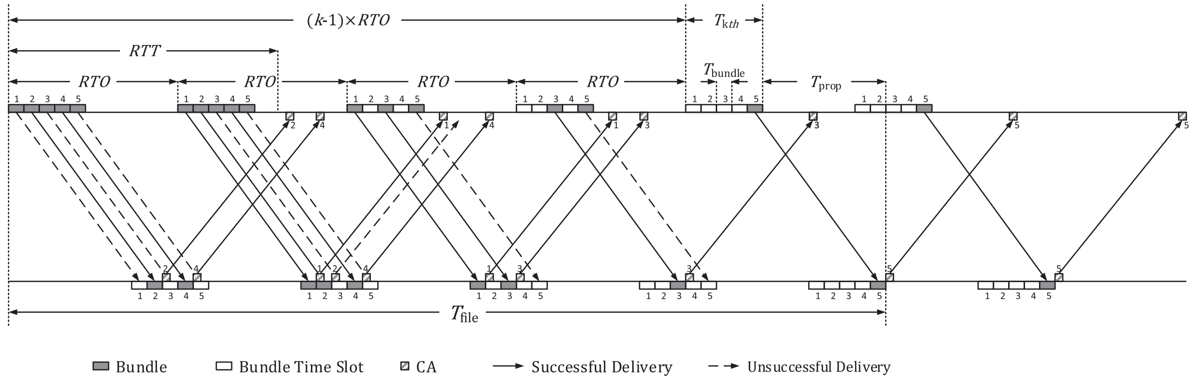

Fig. 1. Scenario of file transmission and retransmissions using BP based on the RTO timer setting (shorter than RTT).

interval plays a key role in data delivery and, thus, causes a significantly different transmission performance, especially in the presence of frequent loss events. Data delivery over a deep-space channel is characterized by highly asymmetric channel rates; in other words, the rate of the uplink channel deployed for transmission of ACK from the earth to the spacecraft or another planet is generally much lower than the rate of the downlink channel deployed for data download in the opposite direction [34]. Channel-rate asymmetry introduces delay for ACK transmissions, leading to additional latency for data delivery and thus a longer RTT.

For the operation of the TCP/IP-based terrestrial Internet, it is reasonable that the RTO timer interval of TCP is generally set to be equal to an estimated RTT with minor variations allowed because of the very short link propagation delay and less lossy channel [i.e., a low bit-error-rate (BER)). However, in the presence of the extremely long RTT over the interplanetary channel in deep space, the transmission with a RTO timer interval set close to RTT as for the terrestrial TCP results in an excessively long waiting time. The long time in waiting for an ACK from a spacecraft in deep space or from a different planet leads to a very long file delivery time. Provided that an extremely large bandwidth-delay product is available for deep-space missions, it also results in underutilization of the channel bandwidth. The situation is aggravated by frequent data losses (caused by the lossy data channel and intermittent connectivity) for which a high data loss rate typically causes multiple retransmission rounds with each additional round taking one RTT.

Based on the aforementioned discussion, it is concluded that the transmission with a RTO timer interval close to an RTT is extremely inefficient for data delivery and channel bandwidth usage in deep-space communications. For a very long time in the future, deep-space communications will still operate with channel bandwidth dedicated for a mission data transmission and with static, prescheduled management procedures, implying that data flow multiplexing and congestion control are not real issues at present and in the near future. Given that this important feature characterizes deep-space communications, it is reasonable to set the RTO timer interval of the DTN protocol much shorter than the RTT for efficient data delivery. With a reasonably shorter RTO timer interval, it will avoid the long waiting time interval between consecutive transmission rounds. It is expected to lead to retransmissions of the data bundles in a nearly continuous manner and achieve the higher transmission efficiency and maximum bandwidth usage of the scarce deep-space channel.

In this paper, we present an analytical modeling of an optimal RTO timer setting for the best goodput performance of BP in deep-space communications. The intent is to derive a formula to compute the optimal RTO timer interval (likely shorter than the RTT in a typical deep-space scenario) that will result in the best goodput performance of BP normalized with respect to the total amount of data transmitted in order to achieve successful delivery of an entire file.

IV. PERFORMANCE MODELING FOR BP WITH RESPECT TO RTO TIMER

In this section, an analytical model is built to compute an optimal RTO timer interval of BP in deep-space missions. First, a model is built for the goodput performance of BP with respect to the variation of the RTO timer interval. To evaluate the performance efficiency, the model of goodput is normalized with respect to the total amount of data transmitted. Then, a formula is derived to compute the optimal RTO timer interval that will result in the best normalized goodput performance of BP. Notations we use for the derivation of the model are specified in Table I.

A. Modeling of Goodput Performance of BP With Respect to the RTO Timer Interval

In Fig. 1, a scenario of BP file transmission is presented to illustrate the bundle (re)transmission mechanism based on the RTO timer setting. Based on the discussion in Section III, the RTO timer interval was set shorter than the RTT interval in the scenario in order to model for an optimal RTO timer interval that will result in the best goodput performance of BP in deep-space communications. Because the timer interval was set shorter than the RTT interval, the file is able to be transmitted at least once within a period of RTT. For the sake of simplicity, it is shown in the presented sample scenario in Fig. 1 that the file was transmitted

Table I
Notations

Symbol	Definition
RTO	RTO timer interval of BP custodial bundle
T_{bundle}	Bundle transmission time
k	Number of transmission efforts (or attempts) required for successful delivery of a file
T_{file}	Total file delivery time
$T_{k\text{th}}$	An approximation of the transmission time for the *k*th transmission attempt
L_{file}	Size of a file (in bytes) for transmission
L_{bundle}	Length of a BP bundle in bytes with its header length excluded
N_{bundle}	Number of bundles required to convey an entire file
R_{data}	Transmission rate of data channel
L_{header}	Total overhead of a bundle after being encapsulated by all the layers underneath BP
$L_{\text{UDP-header}}$	Head size of an UDP datagram
N_{frame}	Number of data frames at link layer required for transmission of a bundle
$L_{\text{IP-header}}$	Head size of an IP packet
$L_{\text{link-header}}$	Overhead size of data link layer protocol
γ	Goodput of BP transmission
p	BER of the data transmission (i.e., probability of transmission bit error)
P_{bundle}	Transmission error probability of a bundle
L_{ACK}	Length of a custody acknowledgment in bytes
P_{ack}	Transmission error probability of an ACK bundle
$P_{i\text{th}}$	Probability that a bundle is successfully delivered to the destination and thus released by the sender on the *i*th transmission attempt (after the first RTT interval)
m	Number of transmission efforts made after the first RTT interval for successful delivery of an entire file
D_{release}	Total number of bundles successfully delivered (and thus released by the sender) during the initial RTT interval
D	Total number of data bundles transmitted from the sender to the receiver to ensure successful delivery of a file
D_{total}	Total data load (in bytes) transmitted over the channel to ensure successful delivery of an entire file
D_{N}	Total data load transmitted over the channel after normalized with respect to original file size
γ_{N}	Goodput of BP transmission after normalized with respect to the total data load
$\gamma_{\text{N}-1}$	An upper limit of γ_{N} at various RTO timer intervals (i.e., γ_{N} with $\left\lceil \frac{RTT}{RTO} \right\rceil$ substituted by $\frac{RTT}{RTO}$)
RTO_1	Optimal RTO timer interval with respect to $\gamma_{\text{N}-1}$
RTO_{optimal}	Optimal RTO timer interval with respect to γ_{N}
$RTO_{\text{optimal-l}}$	RTO timer interval corresponding to the peak of $\gamma_{\text{N}}(RTO)$ adjacent to $\gamma_{\text{N}-1}(RTO_1)$ on the *left*
$RTO_{\text{optimal-r}}$	RTO timer interval corresponding to the peak of $\gamma_{\text{N}}(RTO)$ adjacent to $\gamma_{\text{N}-1}(RTO_1)$ on the *right*

twice. The file is conveyed by five bundles, and all the bundles are transmitted in the initial transmission attempt and then retransmitted upon expiration of the individual RTO timer during the first RTT. In the presence of bundle or CA losses over a lossy channel, some of the bundles are re-retransmitted for one or more times upon expiration of their RTO timer. The transmission of the entire file is not successful until all five bundles are successfully delivered at the receiver.

Let RTO be the RTO timer interval of BP custodial bundle. Let T_{bundle} be the bundle transmission time and T_{prop} be the one-way propagation time of the deep-space channel from the sender to the receiver, as shown in the second-last transmission effort in Fig. 1. Assumed that it took k transmission attempts to successfully deliver the entire file. Then, if the processing time, queuing time, and other times are ignored for simplicity, the total file delivery time T_{file} can be approximated as

$$T_{\text{file}} = (k-1) \times \text{RTO} + T_{k\text{th}} + T_{\text{prop}} \tag{1}$$

in which $T_{k\text{th}}$ is an approximation of the transmission time for the kth transmission attempt, as illustrated in Fig. 1.

Let L_{file} be the size of a file in bytes for transmission and L_{bundle} be the length of a BP bundle in bytes with its header length excluded. The number of bundles required to convey the entire file N_{bundle} (i.e., five in the scenario in Fig. 1) can be calculated as $N_{\text{bundle}} = \frac{L_{\text{file}}}{L_{\text{bundle}}}$. The last bundle to be retransmitted in the kth transmission attempt can actually be random (i.e., can be anyone of N_{bundle} bundles) depending on which one is still not successfully delivered after the $(k-1)$ attempts are made. It is shown to be the fifth bundle in the presented scenario. Therefore, taking an average approach, $T_{k\text{th}}$ can be approximated as

$$T_{k\text{th}} = \frac{1}{N_{\text{bundle}}} \sum_{i=1}^{N_{\text{bundle}}} (i \; T_{\text{bundle}}) = \frac{T_{\text{bundle}}}{N_{\text{bundle}}} \sum_{i=1}^{N_{\text{bundle}}} i = \frac{T_{\text{bundle}}}{N_{\text{bundle}}} \frac{N_{\text{bundle}}\,(N_{\text{bundle}}+1)}{2} = \frac{N_{\text{bundle}}+1}{2} T_{\text{bundle}}. \tag{2}$$

Assume that the transmission rate of the data channel is R_{data} and the total overhead of a bundle after being encapsulated by all the layers underneath BP is L_{header}. Then, the bundle transmission time T_{bundle} can be calculated as

$$T_{\text{bundle}} = \frac{(L_{\text{bundle}} + L_{\text{header}})}{R_{\text{data}}}. \tag{3}$$

The total overall header L_{header} can be written as

$$L_{\text{header}} = L_{\text{UDP-header}} + N_{\text{frame}} \times (L_{\text{IP-header}} + L_{\text{link-header}})$$

in which $L_{\text{UDP-header}}$ is the head size of an UDP datagram, N_{frame} is the number of data frames at link layer required for transmission of a bundle, $L_{\text{IP-header}}$ is the head size of an IP packet, and $L_{\text{link-header}}$ is the overhead size of the data link layer protocol.

With the total file delivery time derived in (3), the goodput performance of BP can be derived as

$$\gamma = \frac{L_{\text{file}}}{T_{\text{file}}} = \frac{L_{\text{file}}}{(k-1) \times \text{RTO} + \frac{N_{\text{bundle}}+1}{2} \times \frac{(L_{\text{bundle}}+L_{\text{header}})}{R_{\text{data}}} + T_{\text{prop}}}. \tag{4}$$

Assume that the BER of the data transmission is p, which is a numerical representation of the net overall transmission quality reflecting such factors as signal strength, interplanetary scintillation, and solar wind. Then, the transmission error probability of a bundle P_{bundle} can be calculated as

$$P_{\text{bundle}} = 1 - (1-p)^{8 \times L_{\text{bundle}}}. \tag{5}$$

Similarly, if the length of a CA in bytes is L_{ack}, the transmission error probability of an ACK bundle P_{ack} can be calculated as

$$P_{\text{ack}} = 1 - (1-p)^{8 \times L_{\text{ack}}}. \tag{6}$$

Assuming that the transmission of bundles conforms to a geometrical probability distribution. Let the probability that a bundle is successfully delivered to the destination and thus released from the memory by the sender on the ith transmission attempt after the first RTT is $P_{i\text{th}}$. Then,

For the 1st transmission attempt, $P_{1\text{st}} = (1 - P_{\text{bundle}}) \times (1 - P_{\text{ack}})$.

For the 2nd transmission attempt, $P_{2\text{nd}} = (1 - P_{1\text{st}}) \times (1 - P_{\text{bundle}}) \times (1 - P_{\text{ack}})$.

For the 3rd transmission attempt,

$$\begin{aligned} P_{3\text{rd}} &= (1 - P_{1\text{st}} - P_{2\text{nd}}) \times (1 - P_{\text{bundle}}) \times (1 - P_{\text{ack}}) \\ &= (1 - (1 - P_{\text{bundle}}) \times (1 - P_{\text{ack}}))^2 \times (1 - P_{\text{bundle}}) \\ &\quad \times (1 - P_{\text{ack}}) = (1 - P_{1\text{st}})^2 \times P_{1\text{st}}. \end{aligned}$$

Therefore, for the mth transmission attempt

$$\begin{aligned} P_{m\text{th}} &= (1 - (1 - P_{\text{bundle}}) \times (1 - P_{\text{ack}}))^{m-1} \times (1 - P_{\text{bundle}}) \\ &\quad \times (1 - P_{\text{ack}}) = (1 - P_{1\text{st}})^{m-1} \times P_{1\text{st}}. \end{aligned} \tag{7}$$

Therefore, the number of bundles that are successfully delivered and thus released from the sender's memory by the mth transmission attempt should be $(N_{\text{bundle}} \times P_{m\text{th}})$. Similarly, if the number of bundles to be released from the sender's memory by the $(m+1)$th transmission attempt is fewer than one, i.e., no bundles need to be released by the $(m+1)$th transmission attempt, then the successful delivery of an entire file is achieved by the mth transmission attempt. In other words, if it is true that

$$\Big\{ N_{\text{bundle}} \times (1 - (1 - P_{\text{bundle}}) \times (1 - P_{\text{ack}}))^m \times (1 - P_{\text{bundle}}) \times (1 - P_{\text{ack}}) \Big\} < 1 \tag{8}$$

the mth transmission attempt is the last effort needed for successful delivery of all the bundles beyond the first RTT. Furthermore, there needs m transmission attempts in total beyond the duration of the first RTT to secure successful delivery of an entire file. Using (8), the number of transmission attempts m can be derived as

$$m = \left\lceil \log_{1-(1-P_{\text{bundle}})\times(1-P_{\text{ack}})} \frac{1}{N_{\text{bundle}} \times (1-P_{\text{bundle}}) \times (1-P_{\text{ack}})} \right\rceil. \tag{9}$$

In order to illustrate the m transmission efforts derived in (9) and other efforts needed for successful delivery of the entire file, Fig. 2 reiterates the same transmission scenario presented in Fig. 1 but with a focus on the number of transmission efforts taken during different time periods. As in Fig. 1, it is assumed that k transmission efforts are needed in total for successful delivery of all five bundles. Out of all k efforts, $\lceil \frac{\text{RTT}}{\text{RTO}} \rceil$ efforts are made during the period of the initial RTT, and the rest of them (i.e., m efforts) are made beyond the duration of the first RTT, as illustrated. Therefore, the total number of transmission efforts k needed to

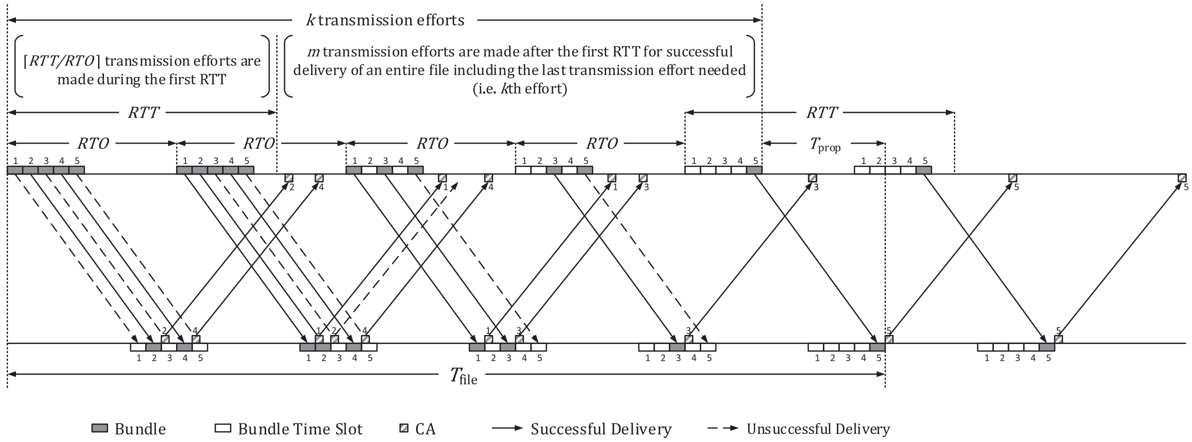

Fig. 2. BP's bundles transmissions and interactions between a sender and a receiver with respect to the RTO timer interval and number of transmission efforts taken.

successfully deliver the entire file can be formulated as

$$k = \left\lceil \frac{\text{RTT}}{\text{RTO}} \right\rceil + m = \left\lceil \frac{\text{RTT}}{\text{RTO}} \right\rceil + \left\lceil \log_{1-(1-P_{\text{bundle}})\times(1-P_{\text{ack}})} \times \frac{1}{N_{\text{bundle}} \times (1-P_{\text{bundle}}) \times (1-P_{\text{ack}})} \right\rceil. \quad (10)$$

B. Derivation of Optimal RTO Timer Interval for Best Normalized Goodput of BP

Let D_{released} be the total number of bundles that are in fact successfully delivered during the initial RTT interval and, thus, are not retransmitted during all the m transmission attempts (beyond the first RTT interval), and it can be formulated as

$$D_{\text{released}} = N_{\text{bundle}} \times (1 - P_{\text{bundle}})(1 - P_{\text{ack}}) \times \sum_{i=1}^{m} \times [1 - (1 - P_{\text{bundle}})(1 - P_{\text{ack}})]^{m-i} \times i. \quad (11)$$

Then, taking an approach of complement, the actual total number of data bundles D that are transmitted from the sender to the receiver to ensure the successful delivery of an entire file can be formulated as

$$D = N_{\text{bundle}} \left(\left\lceil \frac{\text{RTT}}{\text{RTO}} \right\rceil + m \right) - D_{\text{released}}. \quad (12)$$

Therefore, the total amount of data bytes D_{total} that are actually transmitted over the channel to ensure the successful delivery of an entire file can be formulated

$$D_{\text{total}} = N_{\text{bundle}} \times \left\{ \left(\left\lceil \frac{\text{RTT}}{\text{RTO}} \right\rceil + m \right) - (1-P_{\text{bundle}})(1-P_{\text{ack}}) \times \sum_{i=1}^{m} [1-(1-P_{\text{bundle}})(1-P_{\text{ack}})]^{m-i} \times i \right\} \times L_{\text{bundle}}. \quad (13)$$

If the total amount of data in bytes transmitted over the channel is normalized with the respect to original file size, denoted as D_{N}, it can be formulated as

$$D_{\text{N}} = \frac{D_{\text{total}}}{L_{\text{file}}} = \left(\left\lceil \frac{\text{RTT}}{\text{RTO}} \right\rceil + m \right) - (1 - P_{\text{bundle}})(1 - P_{\text{ack}}) \times \sum_{i=1}^{m} [1 - (1 - P_{\text{bundle}})(1 - P_{\text{ack}})]^{m-i} \times i. \quad (14)$$

With the total amount of data over the channel formulated in (14), the goodput performance derived in (4) can be normalized with respect to the total amount of data traffic transmitted as (15), shown at the bottom of this page.

According to (15), if the RTO timer interval (i.e., RTO) is set longer than the RTT interval (i.e., RTT), the normalized goodput performance γ_{N} will be degraded along with an increase of RTO. The performance change implies that for the best normalized goodput performance, the optimal RTO timer interval should not be set longer than the RTT interval, i.e., RTO $\in (0,\ \text{RTT}]$. In other words, the maximum value of RTO should be RTT.

For the ceiling function $\lceil \frac{\text{RTT}}{\text{RTO}} \rceil$ in (15), it has the following formulation

$$\frac{\text{RTT}}{\text{RTO}} \leq \left\lceil \frac{\text{RTT}}{\text{RTO}} \right\rceil < \left(\frac{\text{RTT}}{\text{RTO}} + 1 \right). \quad (16)$$

With the above-mentioned formulation, substituting $\lceil \frac{\text{RTT}}{\text{RTO}} \rceil$ in (15) by $\frac{\text{RTT}}{\text{RTO}}$, (15) can be divided into two different cases depending on the numerical value of m.

For $m = 1$, see (17) shown at the top of next page.

For $m \neq 1$, see (18) shown at the top of next page.

Because of $\frac{\text{RTT}}{\text{RTO}} \leq \lceil \frac{\text{RTT}}{\text{RTO}} \rceil < (\frac{\text{RTT}}{\text{RTO}} + 1)$, $\gamma_{\text{N}-1}$ actually serves as an upper limit of the maxima of γ_{N} at various

$$\gamma_{\text{N}} = \frac{\gamma}{D_{\text{N}}} = \frac{\dfrac{L_{\text{file}}}{\left(\lceil \frac{\text{RTT}}{\text{RTO}} \rceil + m - 1\right) \times \text{RTO} + \frac{N_{\text{bundle}}+1}{2} \times \frac{(L_{\text{bundle}}+L_{\text{header}})}{R_{\text{data}}} + T_{\text{prop}}}}{\left(\lceil \frac{\text{RTT}}{\text{RTO}} \rceil + m\right) - (1 - P_{\text{bundle}})(1 - P_{\text{ack}}) \times \sum_{i=1}^{m} [1 - (1 - P_{\text{bundle}})(1 - P_{\text{ack}})]^{m-i} \times i} \quad (15)$$

$$\gamma_{\mathrm{N}-1} = \frac{L_{\mathrm{file}}}{\left[\mathrm{RTT} + \frac{N_{\mathrm{bundle}}+1}{2} \times \frac{(L_{\mathrm{bundle}}+L_{\mathrm{header}})}{R_{\mathrm{data}}} + T_{\mathrm{prop}}\right] \times \left\{\frac{\mathrm{RTT}}{\mathrm{RTO}} + 1 - (1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}})\right\}} \tag{17}$$

$$\gamma_{\mathrm{N}-1} = \frac{\frac{L_{\mathrm{file}}}{\left(\frac{\mathrm{RTT}}{\mathrm{RTO}}+m-1\right)\times\mathrm{RTO}+\frac{N_{\mathrm{bundle}}+1}{2}\times\frac{(L_{\mathrm{bundle}}+L_{\mathrm{header}})}{R_{\mathrm{data}}}+T_{\mathrm{prop}}}}{\left(\frac{\mathrm{RTT}}{\mathrm{RTO}}+m\right) - (1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}}) \times \sum_{i=1}^{m}\left[1-(1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}})\right]^{m-i} \times i} \tag{18}$$

RTO timer intervals. Therefore, it is reasonable to compute RTO for γ_{N} based on $\gamma_{\mathrm{N}-1}$.

In the case of $m = 1$, according to (17), $\gamma_{\mathrm{N}-1}$is a monotonically increasing function with RTO. Therefore, given the available range of the optimal RTO timer, i.e., RTO $\in$ (0, RTT], the RTO timer interval should be set to the RTT interval for the best performance of $\gamma_{\mathrm{N}-1}$. In other words, the optimal RTO timer interval for γ_{N}, which can be named $\mathrm{RTO}_{\mathrm{optimal}}$, is equal to RTT, i.e., $\mathrm{RTO}_{\mathrm{optimal}} = \mathrm{RTT}$. Furthermore, there are only two transmission attempts needed in total to secure successful delivery of all the data bundles of the file, i.e., $k = 2$, according to $k = \lceil\frac{\mathrm{RTT}}{\mathrm{RTO}}\rceil + m$.

In the case of $m \neq 1$, for the formula developed in (18) (i.e., the function for $\gamma_{\mathrm{N}-1}$), it is reasonable to assume that RTO cannot be zero both mathematically and practically. Mathematically, the function for $\gamma_{\mathrm{N}-1}$ is also differentiable with respect to RTO. Therefore, the optimal RTO timer interval that can maximize the goodput normalized with respect to the total amount of data, named RTO_1, can be formulated by taking the first derivative of $\gamma_{\mathrm{N}-1}$ in (18) with respect to RTO, i.e., by making

$$\frac{d\gamma_{\mathrm{N}\text{-}1}}{d\mathrm{RTO}} = 0. \tag{19}$$

The derivative process with respect to RTO leads to (20), shown at the bottom of this page.

It is found that (21), shown at the bottom of this page, and therefore (22), shown at the bottom of this page.

It is important to note that RTO_1 is an optimal RTO timer interval for $\gamma_{\mathrm{N}-1}$ instead of γ_{N}. $\gamma_{\mathrm{N}-1}(\mathrm{RTO})$ is a mono-peak curve function, which has a single peak with $\mathrm{RTO} = \mathrm{RTO}_1$ while $\gamma_{\mathrm{N}}(\mathrm{RTO})$ is a multi-peak curve function. $\gamma_{\mathrm{N}}(\mathrm{RTO})$ has one peak for every value of RTO that satisfies $\lceil\frac{\mathrm{RTT}}{\mathrm{RTO}}\rceil = \frac{\mathrm{RTT}}{\mathrm{RTO}}$, i.e., for every RTO timer interval that is a factor of RTT, because of the ceiling function in the denominator of γ_{N}. The peaks of $\gamma_{\mathrm{N}}(\mathrm{RTO})$ with RTO values satisfying $\lceil\frac{\mathrm{RTT}}{\mathrm{RTO}}\rceil = \frac{\mathrm{RTT}}{\mathrm{RTO}}$ are equal to the numerical limit of $\gamma_{\mathrm{N}-1}(\mathrm{RTO})$ curve at the same RTO values.

The maximum value of $\gamma_{\mathrm{N}}(\mathrm{RTO})$ at the optimal RTO timer interval should be its highest peak of its curve. Since $\gamma_{\mathrm{N}-1}(\mathrm{RTO})$ has a single peak, the highest peak of $\gamma_{\mathrm{N}}(\mathrm{RTO})$ curve should be the higher of the two peaks that are adjacent to $\gamma_{\mathrm{N}-1}(\mathrm{RTO})$, which is the peak of $\gamma_{\mathrm{N}-1}(\mathrm{RTO})$. The RTO timer interval that leads to the maximum value (i.e., the highest peak) of $\gamma_{\mathrm{N}}(\mathrm{RTO})$ is the optimal RTO timer interval for γ_{N}, which can be named $\mathrm{RTO}_{\mathrm{optimal}}$. The RTO timer interval corresponding to the peak of $\gamma_{\mathrm{N}}(\mathrm{RTO})$ adjacent to $\gamma_{\mathrm{N}-1}(\mathrm{RTO}_1)$ on the *left*, named $\mathrm{RTO}_{\mathrm{optimal-l}}$, is actually the smallest RTO timer interval that satisfies

$$\left\lceil\frac{\mathrm{RTT}}{\mathrm{RTO}_{\mathrm{optimal-l}}}\right\rceil = \left\lceil\frac{\mathrm{RTT}}{\mathrm{RTO}_1}\right\rceil. \tag{23}$$

Similarly, the RTO timer interval corresponding to the peak of $\gamma_{\mathrm{N}}(\mathrm{RTO})$ adjacent to $\gamma_{\mathrm{N}-1}(\mathrm{RTO}_1)$ on the *right*, named $\mathrm{RTO}_{\mathrm{optimal-r}}$, is actually the smallest RTO timer interval that satisfies

$$\left\lceil\frac{\mathrm{RTT}}{\mathrm{RTO}_{\mathrm{optimal-r}}}\right\rceil = \left\lceil\frac{\mathrm{RTT}}{\mathrm{RTO}_1}\right\rceil - 1. \tag{24}$$

The optimal RTO timer interval $\mathrm{RTO}_{\mathrm{optimal}}$, for γ_{N} in (15) in the case of $m \neq 1$, is either $\mathrm{RTO}_{\mathrm{optimal-l}}$ or $\mathrm{RTO}_{\mathrm{optimal-r}}$ whichever makes γ_{N} larger. In a simple

$$(m-1) \times \left\{m - (1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}}) \times \sum_{i=1}^{m}\left[1-(1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}})\right]^{m-i} \times i\right\} - \frac{\mathrm{RTT}\left[\frac{(N_{\mathrm{bundle}}+1)(L_{\mathrm{bundle}}+L_{\mathrm{header}})}{2R_{\mathrm{data}}} + T_{\mathrm{prop}} + \mathrm{RTT}\right]}{\mathrm{RTO}^2} = 0 \tag{20}$$

$${\mathrm{RTO}_1}^2 = \frac{\mathrm{RTT} \times \left[\frac{(N_{\mathrm{bundle}}+1)(L_{\mathrm{bundle}}+L_{\mathrm{header}})}{2R_{\mathrm{data}}} + T_{\mathrm{prop}} + \mathrm{RTT}\right]}{(m-1) \times \left\{m - (1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}}) \times \sum_{i=1}^{m}\left[1-(1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}})\right]^{m-i} \times i\right\}} \tag{21}$$

$$\mathrm{RTO}_1 = \sqrt{\frac{\mathrm{RTT} \times \left[\frac{(N_{\mathrm{bundle}}+1)(L_{\mathrm{bundle}}+L_{\mathrm{header}})}{2R_{\mathrm{data}}} + T_{\mathrm{prop}} + \mathrm{RTT}\right]}{(m-1) \times \left\{m - (1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}}) \times \sum_{i=1}^{m}\left[1-(1-P_{\mathrm{bundle}})(1-P_{\mathrm{ack}})\right]^{m-i} \times i\right\}}} \tag{22}$$

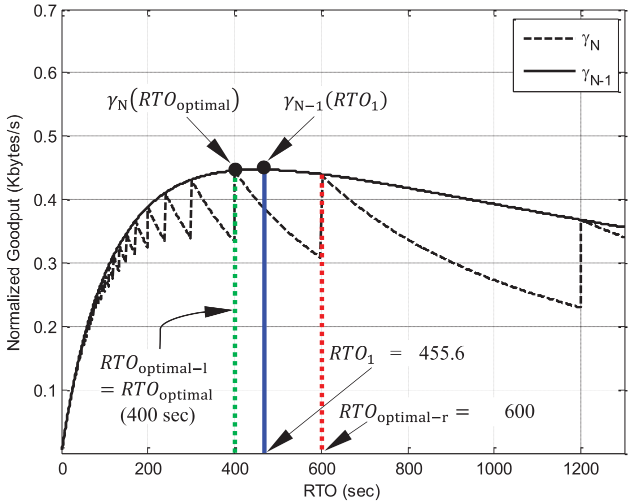

Fig. 3. Illustration of determining an optimal RTO timer interval (i.e., $\text{RTO}_{\text{optimal}}$) for BP transmission of a 10-MB file with a bundle size of 64 KB over a deep-space channel with a data channel rate of 10 Mb/s and a one-way link propagation delay of 10 min, and a BER of 1.5×10^{-6}.

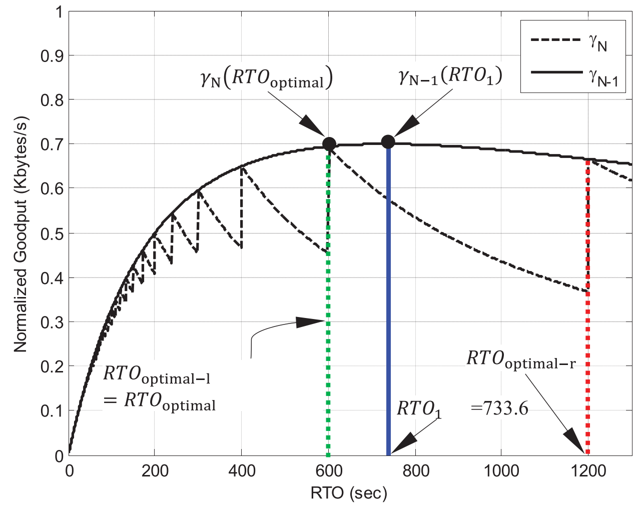

Fig. 4. Illustration of determining an optimal RTO timer interval (i.e., $\text{RTO}_{\text{optimal}}$) for BP transmission of a 10-MB file with a bundle size of 64 KB over a deep-space channel with a data channel rate of 10 Mb/s and a one-way link propagation delay of 10 min, and a BER of 10^{-6}.

formula

$$\text{RTO}_{\text{optimal}} = \begin{cases} \text{RTO}_{\text{optimal}-l} & \gamma_N\left(\text{RTO}_{\text{optimal}-l}\right) > \gamma_N\left(\text{RTO}_{\text{optimal}-r}\right) \\ \text{RTO}_{\text{optimal}-r} & \gamma_N\left(\text{RTO}_{\text{optimal}-l}\right) < \gamma_N\left(\text{RTO}_{\text{optimal}-r}\right) \end{cases} \tag{25}$$

or in a more compact formula

$$\text{RTO}_{\text{optimal}} = \text{RTO}|_{\max\left(\gamma_N|_{\text{RTO}_{\text{optimal}-l}},\ \gamma_N|_{\text{RTO}_{\text{optimal}-r}}\right)}. \tag{26}$$

V. RTO TIMER INTERVALS CALCULATED USING THE MODEL

In this section, the RTO timer intervals calculated using the model in Section III are presented for multiple sample transmission scenarios. To illustrate determination of the optimal RTO timer interval for BP transmission in different scenarios, Figs. 3–5 provide a comparison of the normalized goodput performance of BP from (15) and (18), i.e., γ_N and γ_{N-1}, in transmission of a 10-MB file over a deep-space channel with different channel conditions (i.e., different BERs). For all the scenarios, the data channel rate is 10 Mb/s and the one-way link propagation delay is configured to be 10 min. With a one-way link propagation delay of 10 min, the expected RTT is around 20 min (i.e., 1200 s). Therefore, following the discussion in Section III, RTO timer intervals up to 1200 s are considered in the analysis. The results presented in Figs. 3, 4, and 5 are for transmissions with a bundle size of 64 KB and a channel BER of 1.5×10^{-6}, a bundle size of 64 KB and a channel BER of 10^{-6}, and a bundle size of 50 KB and a channel BER of 10^{-7}, respectively.

As discussed earlier and illustrated in Figs. 3–5, the normalized goodput γ_N is shown as a multipeak curve function while γ_{N-1} (i.e., γ_N with $\lceil\frac{\text{RTT}}{\text{RTO}}\rceil$ substituted by $\frac{\text{RTT}}{\text{RTO}}$) is shown as a mono-peak curve function regardless of the

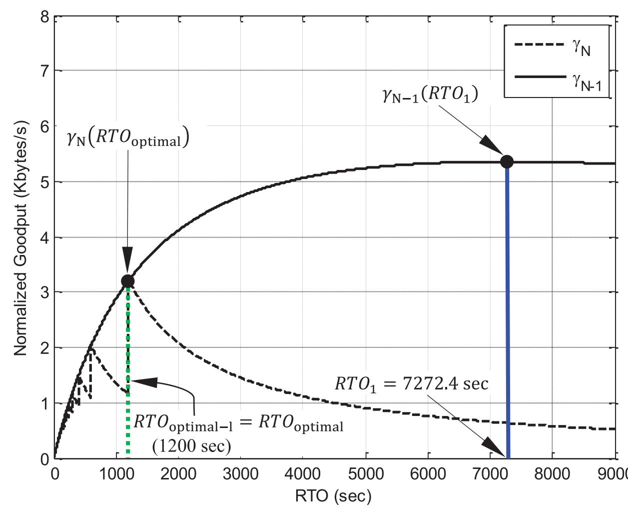

Fig. 5. Illustration of determining an optimal RTO timer interval (i.e., $\text{RTO}_{\text{optimal}}$) for BP transmission of a 10-MB file with a bundle size of 50 KB over a deep-space channel with a data channel rate of 10 Mb/s and a one-way link propagation delay of 10 min, and a BER of 10^{-7}.

transmission configurations. For the transmission with a bundle size of 64 KB and a channel BER of 1.5×10^{-6} illustrated in Fig. 3, it is observed that the maximum (or the peak) of γ_{N-1}, i.e., $\gamma_{N-1}(\text{RTO}_1)$, which is around 450 B/s, is achieved by the RTO timer interval of 455.6 s. In other words, RTO_1 for the transmission with a bundle size of 64 KB and a channel BER of 1.5×10^{-6} is 455.6 s. As the time interval of 400 s is the smallest RTO timer interval that satisfies $\lceil\frac{\text{RTT}}{\text{RTO}_{\text{optimal}-l}}\rceil = \lceil\frac{\text{RTT}}{\text{RTO}_1}\rceil$, it is the interval of $\text{RTO}_{\text{optimal}-l}$ which is adjacent to RTO_1 on the left, i.e., $\text{RTO}_{\text{optimal}-l} = 400$ s. Similarly, as the time interval of 600 s is the smallest RTO timer interval that satisfies $\lceil\frac{\text{RTT}}{\text{RTO}_{\text{optimal}-r}}\rceil = \lceil\frac{\text{RTT}}{\text{RTO}_1}\rceil - 1$, it is the value of $\text{RTO}_{\text{optimal}-r}$ which is adjacent to RTO_1 on the right, i.e., $\text{RTO}_{\text{optimal}-r} = 600$ s. In comparison, the normalized goodput performance with $\mathrm{RTO}_{\mathrm{optimal-l}}$ is slightly higher than that with $\mathrm{RTO}_{\mathrm{optimal-r}}$, i.e., $\gamma_{\mathrm{N}}(\mathrm{RTO}_{\mathrm{optimal-l}}) > \gamma_{\mathrm{N}}(\mathrm{RTO}_{\mathrm{optimal-r}})$. Therefore, $\mathrm{RTO}_{\mathrm{optimal}}$ is equal to $\mathrm{RTO}_{\mathrm{optimal-l}}$ according to (25), and it should be set to 400 s (i.e., $\frac{1}{3}\mathrm{RTT}$) for the maximum goodput (normalized) performance. As illustrated, the RTO timer intervals that are set either shorter than or longer than $\mathrm{RTO}_{\mathrm{optimal}}$ of 400 s result in degradation of the normalized goodput performance of γ_{N}, as $\gamma_{\mathrm{N-1}}$ is a mono-peak curve function.

For the transmission with a bundle size of 64 KB and a channel BER of 10^{-6} in Fig. 4, the maximum of $\gamma_{\mathrm{N-1}}$, around 700 B/s, is achieved by the RTO timer interval of 733.6 s, and therefore, $\mathrm{RTO}_1 = 733.6$ s. As the time interval of 600 s is the smallest RTO timer interval that satisfies $\lceil \frac{\mathrm{RTT}}{\mathrm{RTO}_{\mathrm{optimal-l}}} \rceil = \lceil \frac{\mathrm{RTT}}{\mathrm{RTO}_1} \rceil$, $\mathrm{RTO}_{\mathrm{optimal-l}}$ is equal to 600 s, i.e., $\mathrm{RTO}_{\mathrm{optimal-l}} = 600$ s. As the time interval of 1200 s is the smallest RTO timer interval that satisfies $\lceil \frac{\mathrm{RTT}}{\mathrm{RTO}_{\mathrm{optimal-r}}} \rceil = \lceil \frac{\mathrm{RTT}}{\mathrm{RTO}_1} \rceil - 1$, it is found that $\mathrm{RTO}_{\mathrm{optimal-r}} = 1200$ s, as illustrated in Fig. 4. It is clear that $\gamma_{\mathrm{N}}(\mathrm{RTO}_{\mathrm{optimal-l}}) > \gamma_{\mathrm{N}}(\mathrm{RTO}_{\mathrm{optimal-r}})$ so $\mathrm{RTO}_{\mathrm{optimal}}$ is equal to $\mathrm{RTO}_{\mathrm{optimal-l}}$. Therefore, $\mathrm{RTO}_{\mathrm{optimal}}$ should be set to 600 s (i.e., $\frac{1}{2}\mathrm{RTT}$) for the best goodput (normalized) performance given the transmission conditions, and the RTO timer intervals that are either shorter than or longer than $\frac{1}{2}\mathrm{RTT}$ lead to the performance degradation.

For the transmission with a bundle size of 50 KB and a less lossy channel (i.e., with a BER of 10^{-7}) presented in Fig. 5, following the same procedures used for analysis of the results in Figs. 3 and 4, it is found that $\mathrm{RTO}_1 = 7272.4$ s. The performance comparison indicates that $\mathrm{RTO}_{\mathrm{optimal}}$ should be configured as 1200 s for the best goodput (normalized) performance, i.e., $\mathrm{RTO}_{\mathrm{optimal}} = \mathrm{RTT}$. The setting is compatible with the widely adopted default RTO interval of TCP for the terrestrial Internet, which is mainly because of the less lossy channel. Note that according to the analysis, $\mathrm{RTO}_{\mathrm{optimal-r}}$ is infinitely large for this transmission, and therefore, it is not illustrated in Fig. 5. The variations of $\mathrm{RTO}_{\mathrm{optimal}}$ illustrated in Figs. 3–5 are discussed in details in Section VI.

As in the sample transmission scenarios, Table II provides the optimal RTO timer interval $\mathrm{RTO}_{\mathrm{optimal}}$ (together with RTO_1) obtained from the model for the sample transmission of a 10-MB file over a deep-space channel with a one-way link propagation delay of 10 min and a channel rate of 10 Mb/s. The channel quality is simply selected as “less lossy” (i.e., with a BER of 10^{-7}) or “lossy” (i.e., with the BERs of 10^{-6} and 1.5×10^{-6}). The lossy channel’s BER is widely considered typical of deep-space communications. The selected bundle sizes are 10, 30, 50, and 64 KB. The corresponding total number of transmission efforts k is also provided for each scenario. The optimal RTO timer intervals from these sample transmission scenarios in Table II are verified using file transfer experiments, as noted in Section VI. Note that for the transmissions over a less lossy channel with the bundle sizes of 10 and 30 KB, it is found that there needs only one transmission effort beyond the duration of the first RTT (i.e., $m = 1$) to secure successful delivery of an entire file according to (9) because of high quality of the channel and small bundle sizes, which is a transmission scenario in the case of $m = 1$, as analyzed in Section IV-B, leading to $\mathrm{RTO}_{\mathrm{optimal}} = \mathrm{RTT} = 1200$ s and $k = 2$.

Note that according to the modeling process, the optimal RTO timer interval is directly associated with the length of the RTT interval (e.g., equal to, $\frac{1}{2}\mathrm{RTT}$ or $\frac{1}{3}\mathrm{RTT}$). In other words, the optimal RTO timer interval is inferred from the length of RTT. Therefore, for application of the model presented in this paper, it is assumed that the estimated length of RTT is nearly consistent during the entire file delivery process involving multiple transmission attempts, leading to a consistent RTO timer interval for the best file-delivery performance. Otherwise, if the length of RTT varies due to movement of planets and spacecrafts, link interruption or some other reasons, it is infeasible to obtain a deterministic numerical value for the optimal RTO timer interval of BP, which can be configured for the highest transmission efficiency in deep-space communications.

VI. MODEL VALIDATION OF OPTIMAL RTO TIMER INTERVAL AND TRANSMISSION PERFORMANCE

In this section, we present sample experimental results for the goodput performance of BP with respect to the RTO timer interval. These results are presented in a comparative manner to validate the analytical models built for the optimal RTO timer interval in Section III. The results are measured from file transfer experiments conducted using the testbed. The experimental setup and configurations are briefly described before the numerical results are presented.

A. Experimental Methodology and Configurations

The experimental infrastructure adopted for the proposed validation experiments was emulated using a PC-based space communication and networking testbed (SCNT) [20]. Please refer to [20, Fig. 1] for an illustration of a block diagram of this testbed. According to the experimental evaluations in our previous work [20]–[25], the numerical results given by the SCNT are valid and the testbed works effectively for the performance evaluation of a protocol suite based on realistic data-flow experiments.

This paper focuses on the optimal RTO timer interval that will result in the best transmission performance of BP for reliable data delivery in deep-space communications. Therefore, the file transfer experiments were configured to run “reliable” BP with the custody transfer option enabled over an “unreliable” UDP/IP stack via UDPCL (instead of reliable LTPCL) on the SCNT, i.e., BP/UDPCL/UDP/IP. This stack is simply called BP in this paper. A text file of 10 MB was transmitted using the BP stack via the emulated, relay-based deep-space communication architecture. The file transfer was conducted by running a BP file transmission utility, *bpsendfile*, and a BP file receiving utility, *bprecvfile*, over the protocol stack. The BP and UDPCL protocol implementations adopted for our experiments were provided by the Interplanetary Overlay Network (ION)

Table II
Optimal RTO Timer Interval (i.e., $RTO_{optimal}$) Obtained From the Model for Sample Transmission Scenarios of a 10-MB File Over a Deep-Space Communication Channel With One-Way Link Propagation Delay of 10 min

Transmission Configurations			RTO_1 (sec)	RTO_{optimal} (sec)	Total Number of Transmission Efforts Needed (i.e., k)
Channel Quality		Bundle Size (Kbytes)			
Less Lossy Channel	BER=10^{-7}	10	1200	1200 (=*RTT*)	2 (with m=1)
		30	1200	1200 (=*RTT*)	2 (with m=1)
		50	7272.4	1200 (=*RTT*)	3
		64	6414.5	1200 (=*RTT*)	3
Lossy Channel (Common in deep-space scenarios)	BER=10^{-6}	10	3580.8	1200 (=*RTT*)	4
		30	1627.5	1200 (=*RTT*)	5
		50	936.5	1200 (=*RTT*)	7
		64	733.5	600 (=1/2 *RTT*)	9
	BER=1.5×10^{-6}	10	2895.3	1200 (=*RTT*)	4
		30	996.6	1200 (=*RTT*)	7
		50	612.2	600 (=1/2 *RTT*)	10
		64	455.6	400 (=1/3 *RTT*)	13

distribution v3.5.0 [35], which is the latest BP implementation available at the time these experiments were conducted. ION, which targets space internetworking and deep-space communications, is the software implementations of the DTN protocol suite developed by the JPL, California Institute of Technology, Pasadena, CA, USA.

To emulate inevitable deep-space propagation delay, a one-way link delay of 10 min, which is common over a cis-Martian channel, was introduced to each of the data and ACK channels. As a result, the RTT in a general case is expected to be around 20 min (i.e., 1200 s). Provided that the RTT interval is around 1200 s, various bundle custodial retransmission RTO timer interval ranging up to 1200 s were configured for the experiments. The shortest RTO timer interval was configured to be 100 s, which, as required, is larger than the file transmission time T_{file}. As stated, space links are generally characterized by asymmetric channel rates. To implement the effect of the channel-rate asymmetry on the performance of BP, a high channel ratio 400/1 was configured for the experiments—10 Mb/s for downlink data channel from Mars to earth and 25 Kb/s for the uplink ACK channel in the opposite direction.

Three effective net BERs [i.e., p in (5)]—10^{-7}, 10^{-6}, and 1.5×10^{-6} were configured to study the effect of different channel quality on the transmission performance of BP. As described, the "effective net BER" means that the transmission BER of p is a representation of the net overall transmission quality reflecting such factors as transmission signal strength, interplanetary scintillation, and solar wind. As the classical additive white Gaussian noise (AWGN) channel is broadly recognized and adopted as an accurate model for the deep-space channel [36]–[38], the channel BER in our experiments was imposed following a typical AWGN model. The BERs are among the commonly anticipated transmission conditions over deep-space channels [39].

Three bundle sizes in a broad range were selected for transmission of the 10-MB file—10, 50, and 64 KB. The big gap of bundle sizes between 10 and 50 KB was not experimented because it was found that all the bundles in this range lead to the same optimal RTO timer interval, and therefore, the variation of bundle size in this range in the proposed experiments does not give any new insights with respect to what we are concerned in this study. No bundle larger than 64 KB was experimented because 64 KB is the maximum bundle length that can be accommodated by the underlying UDP datagram. The bundle header length is 28 B and the custodial ACK bundle (i.e., CA) length is 99 B. The MTU size at the data link layer [i.e., L_{MTU} in (2)] is configured to be 1500 B, a commonly used size for Ethernet. The choice of this MTU size aligns with the CCSDS recommendation that the size of an IP datagram be kept to no more than 1500 B when UDPCL runs underneath BP [7].

Note that the intent of the proposed file transfer experiments is to validate the model, and the exact numerical values of channel BER and bundle size are not important with respect to the objective of this study. In other words, the model built for the optimal RTO timer interval is expected to be valid regardless of the numerical values of these configured experimental parameters imposed during data delivery.

B. Model Validation and Numerical Results

Figs. 6–8 present a sample comparison of the normalized goodput performance of BP predicted by the model, and measured from the experiments, in transmission of a 10-MB file with different RTO timer intervals for three bundle sizes, 10 KB, 50 KB, and 64 KB, respectively. The file transmissions are run over a deep-space channel with a

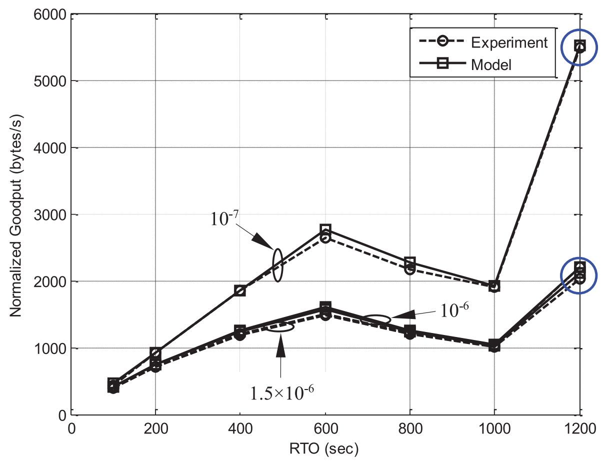

Fig. 6. Comparison of goodput performance of BP normalized with respect to the total data load among different channel quality settings with variations of the RTO timer interval, predicted by the model and observed in the experiments, in transmission of a 10-MB file with a bundle size of 10 KB.

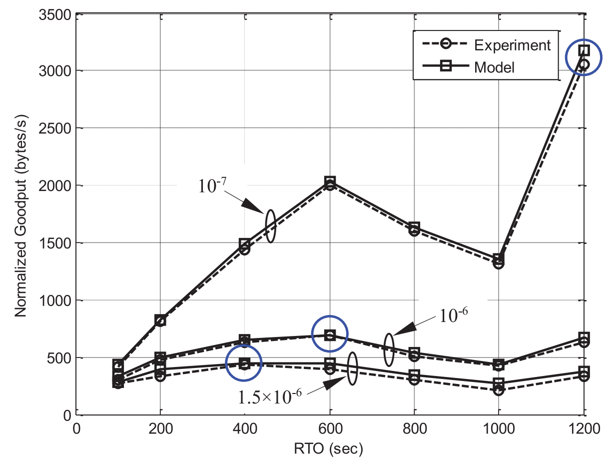

Fig. 8. Comparison of goodput performance of BP normalized with respect to the total data load among different channel quality settings with variations of the RTO timer interval, predicted by the model and observed in the experiments, in transmission of a 10-MB file with a bundle size of 64 KB.

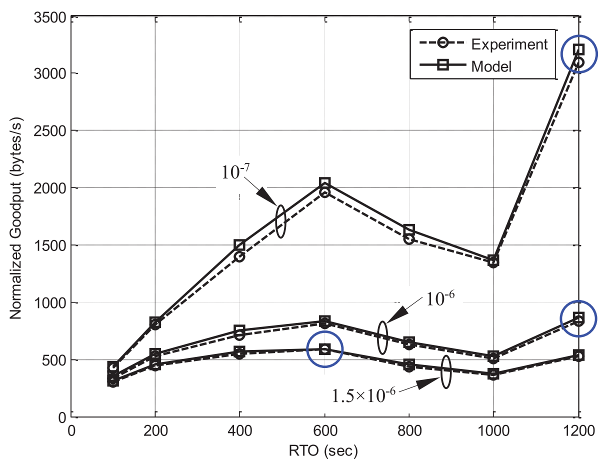

Fig. 7. Comparison of goodput performance of BP normalized with respect to the total data load among different channel quality settings with variations of the RTO timer interval, predicted by the model and observed in the experiments, in transmission of a 10-MB file with a bundle size of 50 KB.

one-way link propagation delay of 10 min and three BERs, 10^{-7}, 10^{-6}, and 1.5×10^{-6}. According to the performance comparisons at three BERs presented in Figs. 6–8, the normalized goodput measured from the experiments and its variation trend with respect to the variation of the RTO timer interval are very close to the model predictions regardless of the channel quality and bundle size. The comparison result proves the validity of the analytical model built to predict the performance of BP with a choice of RTO timer interval ranging up to the RTT interval for file transmission over a deep-space channel. It is observed that the transmissions from the experiments show slightly lower goodput than the model for some configurations. The observation is reasonable as the processing time, queueing time, and other negligible time consumed by the experiments are ignored during the modeling process.

For the transmission configurations with all three bundle sizes, the comparison results show that the optimal RTO timer interval leading to the best normalized goodput performance is obvious. The optimal RTO timer intervals generated from the model, i.e., $\text{RTO}_{\text{optimal}}$ in Table II, lead to the best normalized goodput performance for each transmission configuration, which is in agreement with the results from the file transfer experiment. The agreement indicates that the file transfer experiments confirm the optimality of the RTO timer intervals calculated by the model, and therefore, the model is valid with respect to the optimal RTO timer interval.

According to the analytical results in Table II, with a bundle size of 10 KB, the RTO timer interval for the best normalized goodput should consistently be 1200 s at all three channel BERs, which is equal to the RTT interval at all three channel BERs, i.e., $\text{RTO}_{\text{optimal}} = \text{RTT}$. The comparison in Fig. 6 shows that the RTO timer of 1200 s consistently outperforms all other RTO timer intervals for each transmission, although the one at the BER of 10^{-7} exhibits exceptionally significant performance advantage. Numerically, for the transmission with the bundle size of 10 KB and a BER of 10^{-7}, the best normalized goodput of BP with $\text{RTO}_{\text{optimal}}$ of 1200 s is close to 5500 B/s, as marked. It drastically drops to around 2200 B/s and 2000 B/s along with the significant BER increases to 10^{-6} and 1.5×10^{-6}, respectively. The interval of $\text{RTO}_{\text{optimal}}$ is consistently the same for all three BERs considered in Fig. 6. The reason is that the bundle size of 10 KB is so small that it does not result in significant changes to the file delivery time and thus goodput performance (even with variation of the channel BER from 10^{-7} to 1.5×10^{-6}) has no effect on the interval of $\text{RTO}_{\text{optimal}}$.

Unlike the case with the bundle size of 10 KB, in transmission of much larger bundles, the optimal RTO timer interval varies with the variations of the channel quality. For the transmission with the bundle size of 50 KB in Fig. 7, while the interval of $\text{RTO}_{\text{optimal}}$ is still 1200 s at the BERs of 10^{-7} and 10^{-6}, it drops to 600 s when the BER increases to 1.5×10^{-6}, as predicted by the numerical values in Table II. In other words, the interval of $\text{RTO}_{\text{optimal}}$ is equivalent to an half of the RTT interval, i.e., $\text{RTO}_{\text{optimal}}\frac{1}{2}\text{RTT}$, for a transmission with a BER of 1.5×10^{-6}.

For the transmission of even larger bundles, 64 KB in length, in Fig. 8, more variations of the optimal RTO timer intervals are observed. While $\text{RTO}_{\text{optimal}}$ is still 1200 s at the BER of 10^{-7}, as in Figs. 6 and 7, it drops to 600 s at the BER of 10^{-6} and to 400 s when the BER further increases to 1.5×10^{-6}, proving the variation trend of $\text{RTO}_{\text{optimal}}$ in Table II: given a bundle size, $\text{RTO}_{\text{optimal}}$ tends to decrease along with decrease in the channel quality (i.e., increase in channel BER). The optimal RTO timer interval is expected to decrease for quicker retransmission so that the successful delivery of an entire file can be achieved earlier. Accordingly, the overall file delivery time can be reduced so that the goodput performance can be optimized, which also explains $\text{RTO}_{\text{optimal}}$ for a very small bundle size of 10 KB in Fig. 6 is much longer at all three BERs. Similar to the comparison for the bundle size of 10 KB, the comparisons for the bundle sizes of 50 and 64 KB in Figs. 7 and 8 indicate that the model remains valid with respect to the optimal RTO timer interval for a large bundle.

In a comparison among three BERs for a given bundle size, the normalized goodput performance degrades as the BER increases, leading to the best performance at the BER of 10^{-7} and the poorest performance at the BER of 1.5×10^{-6}, as illustrated in Figs. 6–8. The observation is true for almost all the RTO timer intervals examined, ranging from 100 to 1200 s. The reason is that along with an increase of BER, more data corruption events happen, resulting in more retransmissions efforts needed to ensure successful delivery of the entire file. An increase in retransmission efforts leads to longer file delivery time and additional network traffic, resulting in degradation of the normalized goodput. The increase can be easily verified by checking the variations of the total number of transmission efforts needed k in Table II.

To provide a better view of the BP transmission performance with respect to variation in bundle size, Fig. 9 presents a sample comparison of the normalized goodput for the offered RTO timer intervals among different bundle sizes for a given channel quality, with a BER of 1.5×10^{-6}. More obviously than in Figs. 6–8, $\text{RTO}_{\text{optimal}}$ is found to be quite different for different bundle sizes. As predicted by the model in Table II, the values of $\text{RTO}_{\text{optimal}}$ are equal to 1200 s, 600 s, and 400 s for the bundle sizes of 10 KB, 50 KB, and 64 KB, respectively. Or, simply, they need to be set equal to RTT, $\frac{1}{2}$RTT, and $\frac{1}{3}$RTT in order to maximize the normalized goodput performance for BP transmission with three different bundle sizes.

In a comparison among all three bundle sizes in Fig. 9, it is obvious that the shorter the bundle, the better the normalized goodput performance for its $\text{RTO}_{\text{optimal}}$ and most other RTO timer intervals, except a very short RTO timer interval (such as 200 s or 100 s), for which the performance

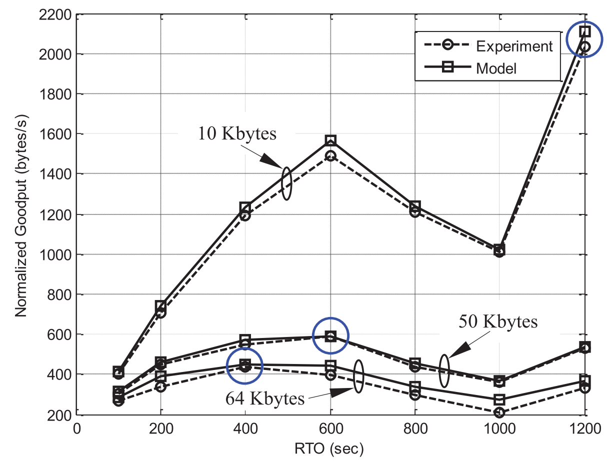

Fig. 9. Comparison of goodput performance of BP normalized with respect to the total data load different bundles with variations of the RTO timer interval, predicted by the model and observed in the experiments, in transmission of a 10-MB file with a BER of 1.5×10^{-6}.

of three bundle sizes tends to merge. The performance variation indicates that the bundle size has less impact on the normalized goodput performance for the short RTO timer intervals, while its impact significantly increases along with the increase of the duration of the RTO timer. This is because the larger the bundle, the higher the likelihood of a corruption event for the larger RTO timer intervals at a given BER, which causes more data to be retransmitted, and thus, more retransmission cycles required. As a result, the goodput performance degrades, as discussed above.

It is also observed that along with the variations of the RTO timer interval, the normalized goodput for a large bundle does not vary as significantly as for a small bundle, leading to further performance advantage of $\text{RTO}_{\text{optimal}}$ over other RTO timer interval for a small bundle. For example, the performance difference (or advantage) of the optimal RTO timer interval over the least optimal one is around 150 B/s for a bundle of size 64 KB and around 300 B/s for bundle of size 50 KB. However, the advantage is significantly higher for the bundle of 10 KB, over 1.7 KB/s. The difference implies that a selection of an optimal RTO timer interval is more significantly important for performance improvement in the transmission of files.

For the goodput performance trend with variation in the RTO timer intervals, it is observed that for all bundle sizes, the transmissions consistently show increase in normalized goodput with an increase of RTO timer interval from 100 to 600 s and from 1000 to 1200 s, although the increase in speed is different for different bundle sizes. However, the transmissions also show performance decrease in response to the increase of the RTO timer interval from 600 to 1000 s. The increase and decrease of normalized performance illustrated in Fig. 9 are determined by the relationship between the achieved goodput performance γ_{N} and the normalized cost of the total data amount placed over the channel D_{N} associated with the variations of $\lceil \frac{\text{RTT}}{\text{RTO}} \rceil$ for a given RTT interval, as reflected by (15) and as predicted by trend of γ_{N} in Fig. 3 for the bundle size of 64 KB.

VII. CONCLUSION

The analytical model developed in this paper, validated by the file transfer experiments, gives an accurate optimal duration for the BP RTO timer (or simply, $\mathrm{RTO}_{\mathrm{optimal}}$) that achieves the best normalized goodput in deep-space communications characterized by an extremely long latency. It is found that, given a bundle size, the effect of channel quality on the optimal RTO timer interval varies. For transmissions with channel quality typical of deep-space communications (with BER $\geq 10^{-6}$) and a reasonably large bundle size, the optimal RTO timer interval should be one half or one third of the RTT interval instead of the widely adopted default RTO setting of TCP for the terrestrial Internet (i.e., the RTT interval). For transmissions of small bundles (e.g., in a range of 5–40 KB), $\mathrm{RTO}_{\mathrm{optimal}}$ is consistently equal to the RTT interval even with variations of channel quality (with BER of $10^{-7}\sim 1.5 \times 10^{-6}$). For the transmission over a nearly clean (or less lossy) channel, the optimal RTO timer interval is also consistently equal to the RTT interval even with variations of the bundle size. With an increase in the channel loss rate, the optimal RTO timer interval tends to decrease—for the best normalized goodput, the larger the bundle size, the shorter the RTO timer interval.

With respect to the effects of bundle size on the performance of the BP transmission, the shorter the bundle size is, the higher the normalized goodput is achieved; the exception to this general rule is a very short RTO timer interval (around 100 s), for which the variations of bundle size have no significant impact on performance. The exception indicates that the bundle size has little impact on the normalized goodput performance for a very short RTO timer interval, but its impact significantly increases along with an increase in the RTO timer interval, highlighting the performance advantages of small bundle sizes. It is also found that the selection of an optimal RTO timer interval is more significantly important for file transmission with small bundle sizes.

VIII. FUTURE WORK

In this study, the average value of the net overall transmission quality (i.e., BER) of a deep-space channel p is fixed during modeling. The impact of the variations of the channel quality (among different transmission rounds) on the derived optimal RTO timer interval needs to be determined and analyzed. This is left as the major future work.

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