Reliable Proactive Retransmission of Bundle Protocol for Deep-Space Communications

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Abstract. As the main protocol of delay/disruption-tolerant networking (DTN) for space, bundle protocol (BP) is designed to establish an overlay network for reliable data/file transfer across highly heterogeneous communication networks. Reliable data/file transmission mechanisms for high performance of BP are presently under development. In this paper, a new transmission approach is proposed for BP for highly reliable data delivery in deep-space communications. The intent is to ensure successful and reliable deep-space file transfer over unreliable space channel which may experience unpredictable or random link disruption events or any other events that lead to burst data losses. The main idea of the proposed approach is to use a hybrid of the *proactive retransmission* and *active retransmission* during file transfer, with each employing different time intervals for the bundle's custodial retransmission timeout (RTO) timer. The reactive retransmission is to provide additional transmission reliability in case the reliability provided by the proactive retransmission was not achieved due to the unpredictable link disruption events. Analytical modeling is presented for performance analysis of the approach, and the built model is validated by the file transfer experiment over a PC-based testbed.

Keywords: Space communications, space networks, satellite communications, wireless networks, DTN

1 Introduction

1.1 Research Background

Developed as an effective networking technology in accommodating the lengthy link disruptions and long link delays that are inevitable in deep-space communications, delay/disruption-tolerant networking (DTN) [1] is a networking architecture which is typically suitable for reliable data/file delivery over unreliable space links. As the main protocol of DTN for space, bundle protocol (BP) [2] is designed to establish an overlay network for reliable file transfer across highly heterogeneous communication networks. BP employs a mandatory store-and-forward mechanism and an optional custody transfer mechanism to achieve reliable data transmission service over a highly unreliable channel. The intent of the joint use of these two transmission mechanisms is to ensure that no data are lost, even in the presence of random link disruption events and/or extremely long propagation delay during data transmission.

In [3], a general DTN architecture and corresponding protocol stacks are presented for use of BP in interoperating highly heterogeneous networks. It is shown that that operate with different networking technologies. BP establishes a networking overlay to interconnect heterogeneous networks that adopts different data transport technologies such as a TCP-based network, a UDP-based network, and a Licklider transmission protocol (LTP)-based network [4, 5]. With the join use of the mentioned two transmission mechanisms together with the nonvolatile permanent memory for data units (named BP *bundles*) at custodial nodes, the interoperation of BP across highly heterogeneous networks needed to sustain data delivery on a hop-by-hop basis is implemented. By this, reliable data delivery is secured even in the presence of lengthy link disruption and extremely long latency.

1.2 Contributions and Novelty

It is widely recognized by the space agencies including National Aeronautics and Space Administration (NASA) that DTN is considered as the only candidate networking technology that is close to maturity for reliable data delivery service in deep-space communications [6]. Reliable data/file transmission mechanisms for high performance of BP are presently under development. In this paper, a new transmission approach is proposed for BP for highly efficient data delivery in deep-space communications. The objective is to ensure successful and reliable deep-space file transfer over unreliable space channel which may experience unpredictable or random link disruption events or a very high channel error rate that lead to burst data losses. The main idea of this proposed approach is to use a hybrid of the *proactive retransmission* and *active retransmission* during file transfer, with the proactive retransmission followed by the active retransmission.

The objective of the *proactive retransmission* is to ensure highly reliable deep-space file transfer within a single communication round-trip interval (i.e., within the first communication round-trip time (RTT)). The supplemental *reactive retransmission* is to provide additional transmission reliability in case the reliability provided by the proactive retransmission was not achieved on data transmission due to the unpredictable link disruption events or any other link events that may lead to burst data losses.

To implement this hybrid transmission approach, two different intervals are employed for the bundle's custodial retransmission timeout (RTO) timer during the file transfer—one for the proactive retransmission and another for the reactive retransmission. The expected minimum number of transmission attempts needed for successful delivery of a file is calculated based on the available space channel quality and the configured bundle size. Analytical modeling is presented for performance analysis of the approach with respect to the resulted total amount of data for successful delivery of a file, file delivery time, and goodput. The model is validated by the file transfer experiment over a PC-based testbed. This study is expected to be practically useful to optimal design and configuration of BP of DTN in providing highly reliable file delivery service in deep-space flight missions.

2 Related Work

A series of studies [3, 7-14] have recently been done in protocol analysis and evaluation for space communications and networks. These studies focus on DTN-based space networks and their extension to deep-space interplanetary internet. Among these studies, the work in [7-8] focuses on DTN's LTP-based networks, and [3, 9-14] focus on BP. The intent of this series of studies is a solid performance analysis and evaluation of the DTN protocols in both analytical and experimental manners.

In [14], a "proactive" retransmission mechanism is proposed for BP for highly efficient data delivery in deep-space communications. The objective of the approach is to ensure successful and reliable deep-space file transfer within a single communication round-trip interval. In details, the expected total number of transmission attempts needed for successful delivery of a file is first calculated based on the available space channel quality and the configured bundle size. Then, the RTO timer interval is set according to the calculated expected number of transmission attempts. Working with the RTO timer interval which control the retransmission period of BP, all the calculated number of transmission attempts will be undertaken within the interval of a single round-trip, i.e., within an interval of RTT.

The "proactive" retransmission mechanism proposed in [14] should work effectively if the communication channel is relatively reliable for which the file transfer unlikely experiences unpredictable or random link disruption events or a very high channel errors that lead to burst data losses. In case of a presence of a lengthy link disruption or any other channel causal events which cause unavailability of data link for a long time, the scheduled multiple proactive retransmission attempts may fail to deliver many or even all the bundles to the receiver but the sender is not aware of it. In this case, the sender assumes that the entire file is successfully delivered at the receiver but is actually not. This results in a catastrophic consequence to the transmission performance of BP for file delivery.

To resolve the potentially severe performance issue of the mechanism proposed in [14], we propose to use a hybrid of the proactive retransmission and active retransmission during the file transfer. In other words, in addition to the mentioned proactive retransmission mechanism, the traditional reactive retransmission mechanism is employed for extra transmission reliability to file transfer. The proposed retransmission approach is illustrated and discussed in Section 3 in a comparison with the one in [14].

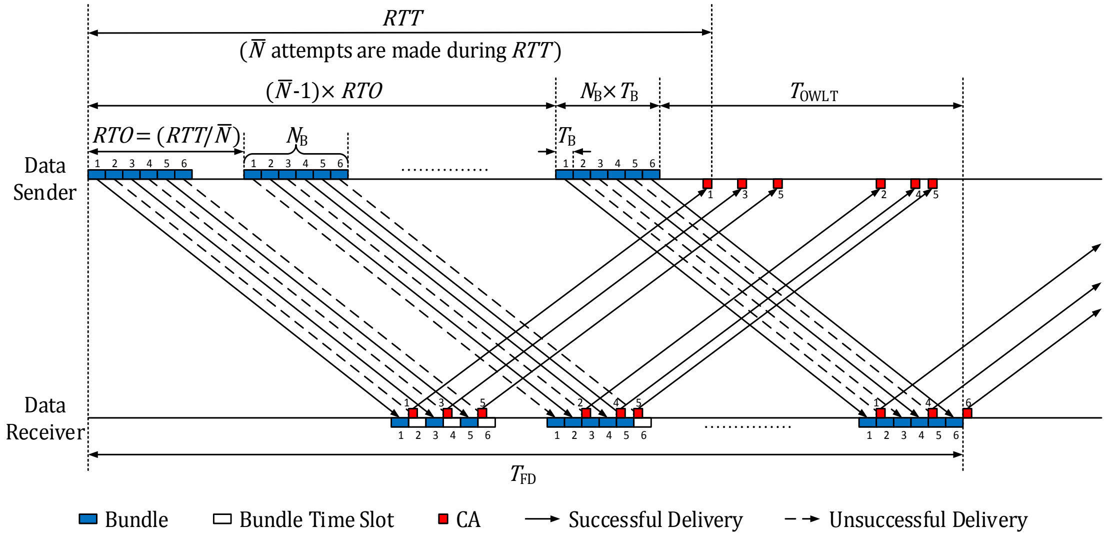

Fig. 1. A scenario of BP data transmission using a proactive retransmission mechanism proposed in [14] for successful file transfer within a single round-trip communication interval.

3 Illustration of the Proposed Reliable Proactive Retransmission of Bundle Protocol

Figure 1 illustrates a recreation of a file transmission scenario using the proactive approach proposed in [14]. Assume that $\bar{N}$ transmission attempts are pre-determined to be statistically sufficient to ensure successful and complete file delivery. Given that the estimated round-trip time length is RTT, all these $\bar{N}$ transmission attempts are arranged to carry out within the interval of RTT by setting the custodial retransmission timeout timer as ($RTT/\bar{N}$), i.e., RTO=($RTT/\bar{N}$). In other words, following an initial transmission (i.e., the first-time transmission) of all the bundles of an entire file, other ($\bar{N}$-1) retransmission attempts are made as soon as their RTO timers expire. It is assumed that even if data loss events (due to channel transmission error) occurred during each attempt, the proactive retransmission can ensure successful delivery of the entire file to the receiver within the first RTT interval. However, as discussed, in case of a presence of a lengthy link disruption or any other channel causal events which cause unavailability of data link for a long time, the multiple retransmission attempts made within the interval of RTT may fail to deliver many or even all the bundles to the destination.

To illustrate the idea of the proposed reliable retransmission approach, a file transmission scenario over a deep-space communication channel using the approach is illustrated in Figure 2. In comparison to the illustration in Figure 1, the proposed reliable proactive retransmission approach adopts a joint use of the proactive retransmission mechanism and reactive retransmission mechanism. Therefore, following the proactive retransmissions of the file within a single communication round-trip interval (i.e., within the first communication RTT), a supplemental reactive retransmission is implemented. With respect to the operation of the proactive retransmissions of the file in the first phase, it is the same as the retransmission process done within the interval of RTT illustrated in Figure 1. In other words, all the bundles of the file are retransmitted for specified times following the calculated RTO timer length, termed as RTO_1, without regard to the acknowledgment from the receiver.

As mentioned, the reactive retransmission designed in the second phase is intended to have additional transmission reliability in case the transmission attempts made in the first phase are not successful for any reason. With respect to the time for retransmission of the lost bundles during the reactive retransmission phase, the first reactive retransmission attempt is made as soon as the CA for any bundles sent in the first phase is received. That is, the first reactive retransmission attempt is made right after a single communication round-trip interval, i.e., RTT. This is because it generally takes the RTT interval to receiver the acknowledgment from the sender. The CA indicates to the sender that which bundles were not successfully delivered or simply, lost, and thus need to be retransmitted. Then, those lost bundles are retransmitted.

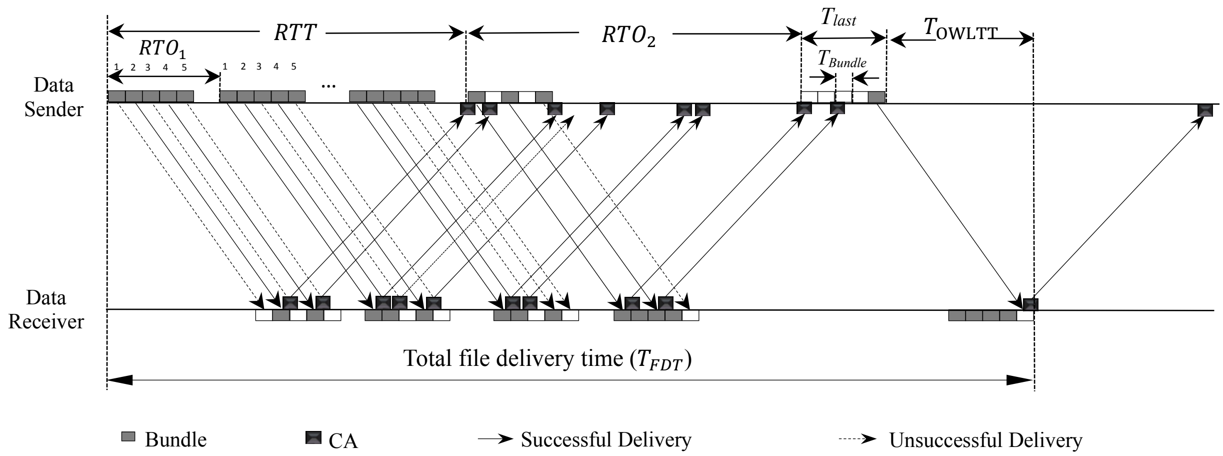

Fig. 2. Illustration of BP transmission using the proposed reliable proactive retransmission approach which adopts a joint use of the proactive retransmission mechanism and reactive retransmission mechanism with each employing different time intervals for the bundle's custodial retransmission timeout (RTO) timer.

Like most automatic-repeat-request (ARQ)-based reliable transmissions, the reactive retransmission is to retransmit the data bundles based on the received acknowledgments or upon expiration of RTO timer. Therefore, the length of the RTO timer is slightly longer than the length of RTT. To differentiate it from the RTO timer length in the first phase, this timer is named as RTO_2. So, if any bundles retransmitted during the reactive transmission phase are lost again, they are re-retransmitted as soon as the CAs are received which is generally done upon expiration of RTO_2.

In comparison to the proactive retransmission approach illustrated in Figure 1, the proposed approach takes a much longer file delivery time. This is the cost for the additional transmission reliability.

4 Performance Modeling for Reliable Proactive Retransmission of BP over Lossy Space Channels

As discussed, the reliable proactive retransmission approach is proposed based on the proactive retransmission mechanism. Therefore, considering their connection, the performance analysis results for the proactive retransmission are revisited before the performance modeling for reliable proactive retransmission is presented. Notations used in the analysis are specified in Table 1.

According to the performance analysis in [14] and based on the time components involved in Figure 1, the total file delivery time, defined as T_{FD}, for the proactive retransmission mechanism can be approximated as a sum of the RTO intervals for the first $(\bar{N}-1)$ attempts, the transmission time of all the bundles of the file in the last round, and the one-way link propagation time in the last round, T_{OWLT}. It is reiterated as

$$T_{FD} = (\bar{N}-1) \times RTO + N_B \times T_B + T_{OWLT} \tag{1}$$

in which

$\bar{N}$ is the average number of the transmission attempts to be carried out by the sender,

RTO is the time-out interval for custodial retransmission timer,

N_B is the number of data bundles that convey the entire file, and

T_B is the bundle transmission time.

The average number of the transmission attempts to be carried out by the sender, $\bar{N}$ in (1), is derived as

Table 1. Notations used during the derivation of the model.

Symbol	Definition
RTO	RTO time interval of BP custodial bundle
RTO_1	RTO time interval of BP custodial bundle within the first RTT
RTO_2	RTO time interval of BP custodial bundle beyond the first RTT
$\overline{N}$	Average number of the transmission attempts
N_B	Number of data bundles that convey the entire file
T_B	Bundle transmission time
T_{OWLT}	Link propagation time
T_{FD}	Total file delivery time
p	BER of the data transmission
L_F	Size of a file (in bytes) for transmission
L_B	Size of a bundle
L_{BHD}	Bundle header length
L_{UHD}	UDP head length
L_{IHD}	IP head length
L_{MTU}	Size of the maximum transmission unit (MTU) of the data link
L_{EACK}	Length of an encapsulated CA at the link layer
P_{ACK}	Transmission error probability of an ACK bundle
P_B	Transmission error probability of a bundle
P_{Round}	Probability that a bundle is successfully delivered and its corresponding CA is successfully received
L_{EB}	Size of an encapsulated bundle
R_D	Downlink channel rate available for data transmission
R_{ACK}	Uplink channel rate available for CA transmission
L_{B-Min}	Minimum bundle size
k	Number of transmission attempts within the first RTT
m	Number of transmission attempts beyond the first RTT
n	Total number of transmission attempts
N	Average number of the transmission attempts needed for the proposed reliable proactive retransmission mechanism
T_{FDT}	Total file delivery time for the proposed reliable proactive retransmission mechanism
T_{last}	Transmission time taken in the last round
γ	Goodput of BP transmission
D_N	Total data load transmitted after normalized with respect to the file size
$N_{B(i)}$	Number of bundles that are in error in transmission round i
$D_{(i)}$	Amount of data that are in transmission round i
D_{total}	Total data load transmitted to ensure successful delivery of an entire file
γ_N	Goodput of BP transmission after normalized with respect to the total data load

$$\overline{N} = \left\lceil -log_{1-(1-p)^{8\times\left[L_B+L_{BHD}+L_{UHD}+\left\lceil\frac{L_B+L_{BHD}+L_{UHD}}{L_{MTU}-L_{IHD}}\right\rceil\times(L_{IHD}+L_{LHD})\right]}} \left\lceil\frac{L_F}{L_B}\right\rceil \right\rceil \quad (2)$$

in which

p is the channel bit-error-rate (BER) of the data transmission which represents the net overall transmission quality,

L_F is the size of a file in bytes that need to be transmitted from the sender to the receiver,

L_B is the size of a bundle, and

$L_B + L_{BHD} + L_{UHD} + \left\lceil \frac{L_B+L_{BHD}+L_{UHD}}{L_{MTU}-L_{IHD}} \right\rceil \times (L_{IHD} + L_{LHD})$ denotes the length of an encapsulated bundle in bytes after being encapsulated by all the layers (underneath BP) in which L_{BHD}, L_{UHD}, L_{IHD}, and L_{LHD} are the bundle header length, the UDP head length, the IP head length, and the overhead length of the data link layer protocol, respectively, and L_{MTU} is the size of the maximum transmission unit (MTU) of the data link for transmission. Note that $1-(1-p)^{8\times\left[L_B+L_{BHD}+L_{UHD}+\left\lceil \frac{L_B+L_{BHD}+L_{UHD}}{L_{MTU}-L_{IHD}} \right\rceil \times (L_{IHD}+L_{LHD})\right]}$ is actually the probability of error in delivering an encapsulated bundle.

With the formula for $\bar{N}$ plugged in (1), T_{FD} is reformulated in [14] as

$$T_{FD} = \left\{ \left\lceil -\log_{1-(1-p)^{8\times\left[L_B+L_{BHD}+L_{UHD}+\left\lceil \frac{L_B+L_{BHD}+L_{UHD}}{L_{MTU}-L_{IHD}} \right\rceil \times (L_{IHD}+L_{LHD})\right]}} \left\lceil \frac{L_F}{L_B} \right\rceil \right\rceil - 1 \right\} \times RTO + \left\lceil \frac{L_F}{L_B} \right\rceil \times \frac{L_B + L_{BHD} + L_{UHD} + \left\lceil \frac{L_B + L_{BHD} + L_{UHD}}{L_{MTU} - L_{IHD}} \right\rceil \times (L_{IHD} + L_{LHD})}{R_D} + T_{OWLT} \tag{3}$$

As discussed in [14], there is a maximum value of the time-out interval for custodial retransmission timer, RTO. The length of RTO can be configured by the sender to have all the bundles of the file successfully delivered at the receiver within the first round-trip communication interval. This length is determined by $\bar{N}$ and the interval of RTT within which all the transmission attempts can be configured and carried out by the sender. In addition, in order to avoid unnecessary data traffic or even traffic congestion on the data channel, the retransmission of the bundles of the file should not occur prior to the completion of the initial transmission or the previous round of retransmission attempt. This means that the length of RTO has to be configured larger than the length of T_F. Therefore, with both bounds taken into consideration, the setting range of RTO has to meet the following requirement

$$\left\{ \frac{L_B + L_{BHD} + L_{UHD} + \left\lceil \frac{L_B + L_{BHD} + L_{UHD}}{L_{MTU} - L_{IHD}} \right\rceil \times (L_{IHD} + L_{LHD})}{R_D} \times \left\lceil \frac{L_F}{L_B} \right\rceil \right\} < RTO \le \left\{ \frac{RTT}{\left\lceil -\log_{1-(1-p)^{8\times\left[L_B+L_{BHD}+L_{UHD}+\left\lceil \frac{L_B+L_{BHD}+L_{UHD}}{L_{MTU}-L_{IHD}} \right\rceil \times (L_{IHD}+L_{LHD})\right]}} \left\lceil \frac{L_F}{L_B} \right\rceil \right\rceil} \right\} \tag{4}$$

In Figure 2, a scenario of BP file transmission using the proposed reliable proactive retransmission approach which adopts a joint use of the proactive retransmission mechanism and reactive retransmission mechanism, with each employing different time intervals for the bundle's custodial RTO timer, is shown. For the sake of simplicity, the scenario is shown for the transmission of file conveyed by five bundles.

As shown in Figure 2, the file is transmitted three times within the first *RTT*, and corresponding CA reaches the data sender beyond the first *RTT* interval. For those bundles that are successfully delivered, since their corresponding CAs are received, the bundles are released at the data sender. The remaining bundles of the file are retransmitted beyond the first *RTT*. Therefore, the number of bundles transmitted for the fourth time (i.e., the first time after the first *RTT*) in Figure 2 is the number of bundles that failed for the first transmission attempt. After the bundle's retransmission time-out timer RTO_2 expires, the data sender will retransmit the remaining bundles until the data receiver receives all the bundles.

Let L_{EACK} be the length of an encapsulated CA at the link layer. Then, L_{EACK} should be simply formulated as the lengths of an encapsulated CA bundle in bytes after being encapsulated by all the layers (underneath BP)

$$L_{EACK} = L_{ACK} + L_{BHD} + L_{UHD} + \left\lceil \frac{L_B + L_{BHD} + L_{UHD}}{L_{MTU} - L_{IHD}} \right\rceil \times (L_{IHD} + L_{LHD}) \tag{5}$$

Then, the probability of error in delivering a CA, P_{ACK}, can be formulated as

$$P_{ACK} = 1 - (1-p)^{8\times L_{EACK}} = 1 - (1-p)^{8\times\left[L_{ACK}+L_{BHD}+L_{UHD}+\left\lceil\frac{L_B+L_{BHD}+L_{UHD}}{L_{MTU}-L_{IHD}}\right\rceil\times(L_{IHD}+L_{LHD})\right]} \tag{6}$$

Similarly, define L_{EB} as the size of an encapsulated data bundle, and the probability of error in delivering an encapsulated data bundle, termed as P_B, can be formulated as $P_B = 1-(1-p)^{8\times L_{EB}} = 1-(1-p)^{8\times\left[L_B+L_{BHD}+L_{UHD}+\left\lceil\frac{L_B+L_{BHD}+L_{UHD}}{L_{MTU}-L_{IHD}}\right\rceil\times(L_{IHD}+L_{LHD})\right]}$. Then, the probability that a bundle is successfully delivered and its corresponding CA is successfully received can be written as

$$P_{Round} = (1-P_B)\times(1-P_{ACK}) \tag{7}$$

For transmission of multiple bundles over highly asymmetric channels, all the CAs except the first one need to wait to be transmitted because of the delayed transmission of the previous CAs caused by reduced ACK channel rate. Assume that the downlink channel rate available for data transmission is R_D and the uplink channel rate available for CA transmission is R_{ACK}. To avoid the delay of CAs due to channel-rate asymmetry, there is a limit to the minimum bundle size, named L_{B-Min}. According to the previous study [12], L_{B-Min} is formulated as

$$L_{B-Min} = \frac{L_{EACK}\times R_D}{R_{ACK}} - L_{BHD} \tag{8}$$

Let $k = \left\lceil\frac{RTT}{RTO_1}\right\rceil$ and the number of transmission attempts beyond the first RTT is m. Then, the total number of transmission attempts during the entire file delivery, n, can be written as $n = k + m$.

Let $N_{B(i)}$ be the number of bundles that are received in error in transmission round i. Since the CAs of the first k transmission attempts have not reached to the data sender, the number of bundles transmitted for each transmission attempt from the first attempt to the *k*th attempt are N_B. The CAs of the first transmission attempt arrive at the data sender beyond the first RTT interval, but the CAs of the subsequent transmissions made within the first RTT interval do not arrive the sender by that time. Therefore, the number of bundles transmitted in the $(k+1)$th attempt can be formulated as $N_{B(k+1)} = N_B\times(1-P_{Round})$. For the $(k+2)$th transmission attempt, one RTO_2 timer interval has passed since the $(k+1)$th transmission made. Therefore, the CAs of the first $(k+1)$ transmission efforts arrive at the data sender. The bundles transmitted in the $(k+2)$th attempt are those failed in the first $(k+1)$ transmission efforts, and it can be formulated as $N_{B(k+2)} = N_B\times(1-P_{Round})^{k+1}$. Then, for the $(k+m)$th transmission attempt, $N_{B(k+m)}$ can be formulated as $N_{B(k+m)} = N_B\times(1-P_{Round})^{k+m-1}$. Continuing with this iterative procedure, $N_{B(k+m+1)}$ can be formulated as $N_B\times(1-P_{Round})^{k+m}$.

Similarly, if the number of bundles to be released from the sender's memory by the $(k+m+1)$th transmission attempt is fewer than one, i.e., that is $N_{B(k+m+1)} < 1$ or $N_B\times(1-P_{Round})^{k+m} < 1$, it implies that no bundles need to be released by the $(k+m+1)$th transmission attempt. This is an indication that the successful delivery of an entire file is achieved by the $(k+m)$th transmission attempt. Let n be the total number of transmission attempts, which satisfies $n = k+m$. Accordingly, a formula can be derived to compute n as

$$n > \left\lceil -log_{(1-P_{Round})} N_B \right\rceil \tag{9}$$

Then, the average number of the transmission attempts to be carried out by the sender, N, can be derived as

$$N = \left\lceil -log_{(1-P_{Round})} N_B \right\rceil \tag{10}$$

The file delivery time is mainly composed of the first RTT, file retransmission time, one-way file propagation time, and the time sent by the last bundle in the last transmission round. Then, the total file delivery time T_{FDT} for the proposed reliable proactive transmission approach can be approximated as

$$T_{FDT} = RTT + (m-1)\times RTO_2 + T_{OWLT} + T_{last} \tag{11}$$

in which T_{last} is an approximation of the transmission time for the last transmission attempt, as illustrated in Figure 2. The last bundle to be retransmitted in the last transmission attempt can actually be random (i.e., can be anyone of N_B bundles) depending on which one is still not successfully delivered after the n attempts are made. Then, T_{last} can be formulated as $\frac{1}{N_B} \times \sum_{i=1}^{N_B} \frac{i \times L_B}{R_D}$.

With the total file delivery time T_{FDT} derived, the goodput performance can be written as $\gamma = \frac{L_F}{T_{FDT}}$. Taking into account the impact of the total amount of data transmitted, the goodput normalized with respect to the total amount of data sent, termed as γ_N, can be formulated as $\gamma_N = \frac{\gamma}{D_N}$ in which D_N is the total data load transmitted over the channel after normalized with respect to the file size. D_N can actually be written as $\frac{D_{total}}{L_F}$ in which D_{total} is the total data load (in bytes) transmitted over the channel to ensure successful delivery of an entire file. The total data load transmitted over the channel includes the amount of data in the first k transmission attempts, the $(k+1)th$ transmission attempt, and the subsequent $(m-1)$ transmission attempts.

Let $D_{(i)}$ be the amount of data that are transmitted in transmission round i. Since the number of bundles for each transmission attempt from the first to the kth are N_B, the amount of data can be calculated as $k \times N_B \times L_{EB}$. The amount of data transmitted in the $(k+1)$th attempt can be formulated as $D_{(k+1)} = (1 - P_{Round}) \times N_B \times L_{EB}$. For the $(k+2)$th transmission attempt, the amount of data can be formulated as $D_{(k+2)} = (1 - P_{Round})^{k+1} \times N_B \times L_{EB}$.

Continuing with this iterative procedure, for the $(k+\mathrm{m})$th transmission attempt, $D_{(k+m)}$ can be derived as $(1 - P_{Round})^{k+m-1} \times N_B \times L_{EB}$. 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 as

$$D_{total} = k \times N_B \times L_{EB} + (1 - P_{Round}) \times N_B \times L_{EB} + \sum_{i=1}^{m-1} (1 - P_{Round})^{k+i} \times N_B \times L_{EB} \tag{12}$$

There is a limit to the numerical value of m. In other word, no matter within or beyond the first RTT interval, there will be at least one transmission attempt made, that is $0 < m < n - 1$. At the same time, k should satisfy $\frac{RTT}{RTO_1} \leq k < \frac{RTT}{RTO_1} + 1$. Therefore, with the total amount of data over the channel formulated in (12), the total file delivery time T_{FDT} in (11), and the related formulations mentioned above, the normalized goodput γ_N can be formulated as

$$\gamma_N = \frac{N_B \times {L_B}^2}{\left(\left\lceil \frac{RTT}{RTO_1} \right\rceil + (1 - P_{Round}) + \sum_{i=1}^{m-1} (1 - P_{Round})^{\left\lceil \frac{RTT}{RTO_1} \right\rceil + i}\right) \times L_{EB}} \times \frac{1}{RTT + (m-1) \times RTO_2 + T_{OWLT} + T_{last}} \tag{13}$$

5 Numerical Experimental Results and Model Validation

In this section, the numerical results of the file transfer experiments over the testbed are presented to validate the predictions of the analytical model. The experimental infrastructure and the protocol configurations are introduced before the numerical results are presented.

5.1 Overview of Experimental Infrastructure and Configurations

The performance model built in Section 4 is validated through file transfer experiments using an experimental infrastructure that emulates communication in a deep-space operational environment. The experimental infrastructure is the PC-based space communication and networking testbed (SCNT) [7]. The SCNT infrastructure was validated through a series of our previous studies in performance evaluation of a protocol suite proposed for space networks and deep-space communications [7-14]. For a detailed description of it, refer to [7].

The protocol implementation of BP used for the experiments was adapted from the Interplanetary Overlay Network

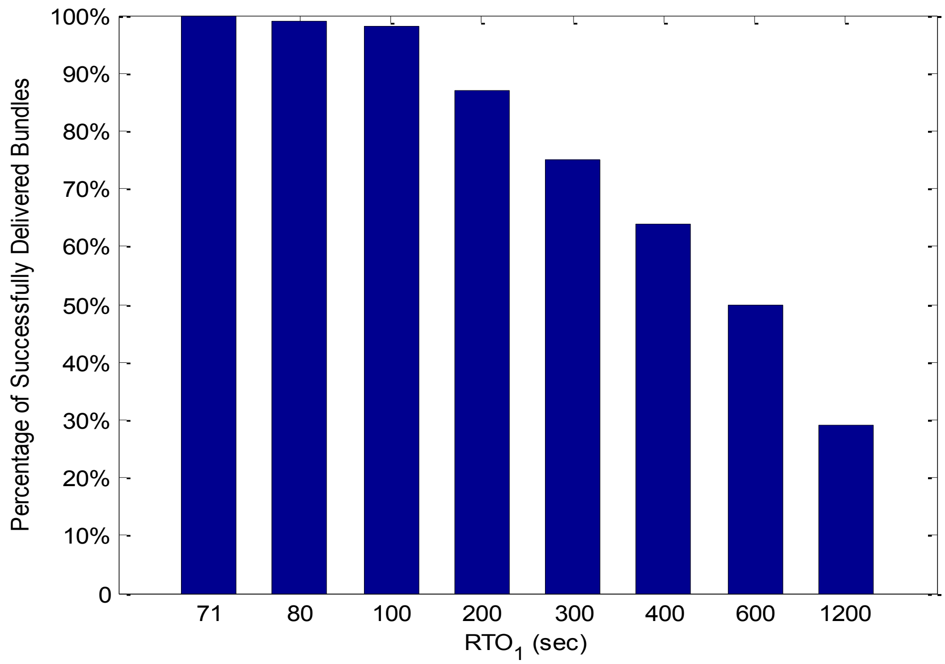

Fig. 3. Comparison of the percentage of successfully transferred bundles in transmitting a 10-Mbyte file with different intervals of RTO_1 over a deep-space channel with link delay of 10 minutes and a BER of 5×10^{-6}, asymmetric channel ratio of 300/1 and a bundle of 30 Kbytes.

(ION) distribution v3.6.2. ION is a software implementation of the DTN protocol suite for space networks and deep-space communications developed by NASA's JPL [15]. UDP, IP and Ethernet were adopted to serve at the underlying convergence layer, network layer and data link layer, respectively. The experiments were run with the bundle with various sizes ranging from 30 Kbytes to 64 Kbytes.

A one-way delay of 600 sec, which is common over a deep-space channel, was introduced to each of the data and ACK channels to emulate the signal propagation delay in deep space. This leads to a length of RTT approximately around 1200 sec. The effect of the channel-rate asymmetry on file transmission was implemented by configuring a high channel speed ratio (CR), 300/1, resulting from a downlink channel rate of 2 Mbps and an uplink channel rate of 6.7 Kbps. A text file of 10 Mbyte is transmitted from the sender to the receiver by running BP together with associated protocols to measure the performance of the protocol.

Provided that the length of RTT is 1200 sec, the interval of RTO_2 is fixed to be slightly higher than 1200 sec. However, a wide range of RTO_1 intervals, from 47 sec to 1200 sec, are experimented.

5.2 Experimental Results and Model Validation

Figure 3 presents a comparison of the percentage of successfully delivered bundles using the proposed reliable proactive retransmission approach in transmitting a 10-Mbyte file with different intervals of RTO_1 over a deep-space channel with link delay of 10 minutes and a BER of 5×10^{-6}, asymmetric channel ratio of 300/1 and a bundle of 30 Kbytes. It is observed in Figure 3 that the smaller the file transmission interval RTO_1 within a single RTT is configured, the more the number of transmission attempts within a single RTT time are made. In other words, more transmission attempts are made by configuring a smaller RTO_1 timer interval within a single RTT time. With more transmission attempts made, the higher the percentage of bundle successful transmission at the end of the RTT time is achieved. This means that with k transmission attempts made, more bundles are successfully delivered. As a result, the file delivery time decreases, and the efficiency of file transfer is improved.

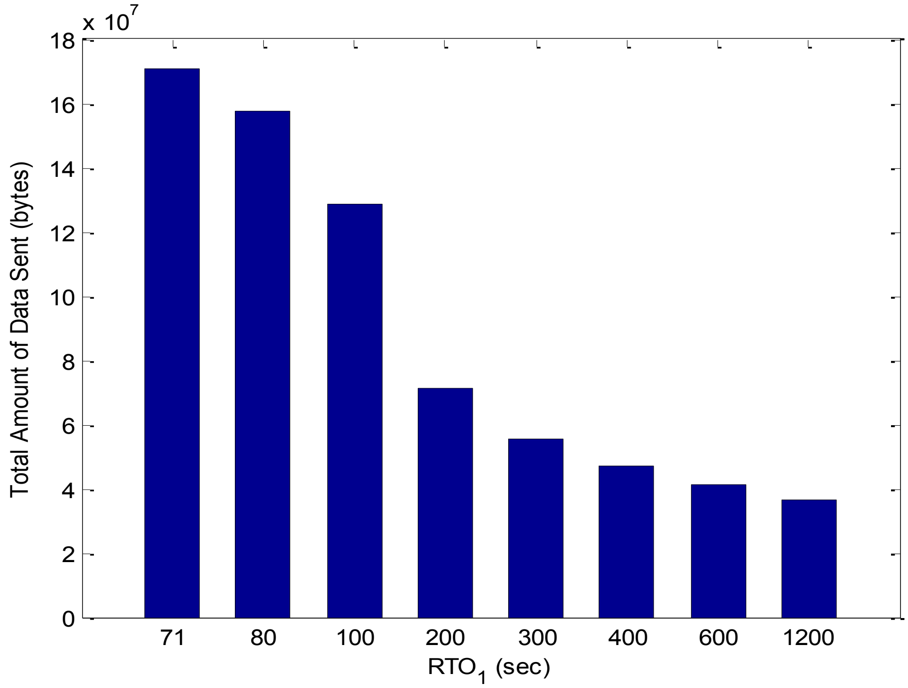

Fig. 4. Comparison of the total amount of data sent in transmission of a 10-Mbyte file with different intervals of RTO_1 over a deep-space channel with link delay of 10 minutes, a BER of 5×10^{-6}, asymmetric channel ratio of 300/1 and a bundle of 30 Kbytes.

Figure 4 presents a comparison of the total amount of data sent by a file with different RTO_1 timer interval within a single RTT time. It can be observed that as the number of transmissions within a single RTT time increases, the total amount of data sent increases rapidly.

Figures 5 and 6 present sample comparisons of the normalized goodput performance of BP with variations of RTO_1 timer interval, predicted by the model and observed in the experiments, in transmission of a 10-Mbyte file with a BER of 5×10^{-6} and bundle sizes of 30 Kbytes and 58 Kbytes, respectively. Both bundle sizes are larger than the required minimum bundle size, L_{B-Min}, to avoid the ACK delay. The numerical value of L_{B-Min} is 29.6 Kbytes according to (8). It is observed that in both Figure 5 and Figures 6, the predicted numerical values of the model match well with those measured from the experiments for all the configured intervals of RTO timer regardless of the bundle size. This indicates that the realistic file transfer experiments validate the model. In addition, the numerical value of the model is slightly higher because some minor delay components such as queue delay and processing delay are ignored when the total file delivery time is modeled.

In comparison, the optimal setting of RTO_1 timer interval which achieves the highest normalized goodput performance of BP is found to be different for two bundle sizes. For the bundle size of 30 KB, the optimal setting of RTO_1 is very short, around equal to 75 sec. With the bundle size significantly increased to 58 Kbytes, the optimal setting increases to a much larger value which is around 600 sec, a half of the RTT length.

The difference in the optimal setting of RTO_1 timer interval for two different bundles are reasonable. Considering that the length of RTO has to be configured larger than the length of T_F, the number of transmission attempts in the first RTT (i.e., during the proactive retransmission) should not exceed twenty-seven. As defined, the main factors that affect the normalized goodput performance are the file delivery time and the total data load over the channel. When the bundle size is 30 Kbytes, it can be calculated from (10) that the total transmission attempts is seventeen, which is less than twenty-seven. So, as many transmissions as possible should be made within the first RTT so that the file delivery time can reach the minimum which can lead to the highest normalized goodput. It can be calculated that $RTO_1 \approx \left\lceil \frac{1200}{17-1} \right\rceil = 75$ sec, which is fully consistent with the variation trend in Figure 5.

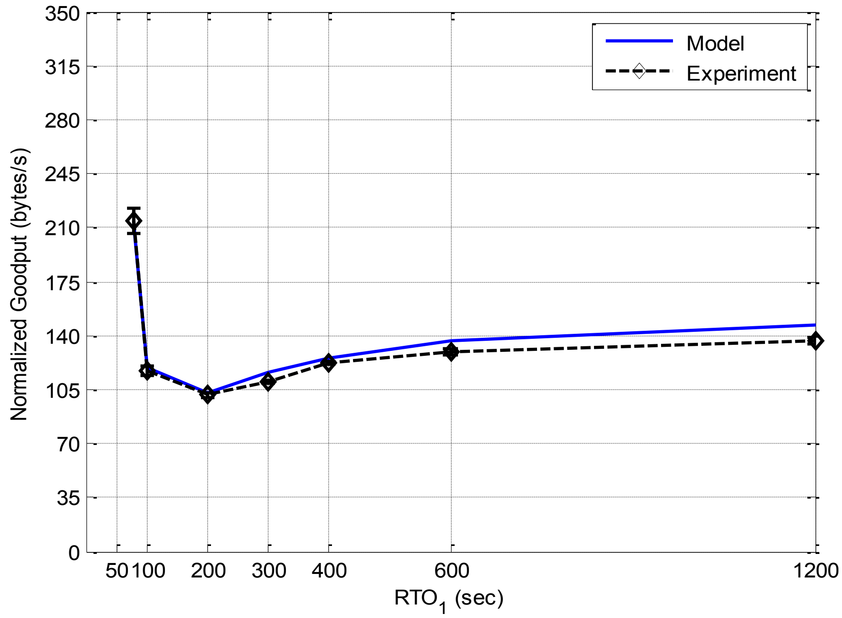

Fig. 5. Comparison of normalized goodput performance of BP with variations of RTO_1 timer interval, predicted by the model and observed in the experiments, in transmission of a 10-Mbyte file with a BER of 5×10^{-6} and a bundle size of 30 Kbytes.

In comparison, for the much larger bundle size of 58 Kbytes, the total transmission attempts are fifty-three which is greater than twenty-seven. Therefore, multiple transmissions must be performed within the first RTT during the proactive retransmission phase and after the first RTT during the reactive retransmission phase. By this, the file delivery time and the total data load over the channel greatly increase. This implies that the total data load has the greatest impact on the normalized goodput. Therefore, for transmissions with a lossy channel typical of deep-space communications and a reasonably large bundle size, as many transmission attempts as possible should be made beyond the first RTT interval so that the total data load can reaches the minimum. Considering the impact of file delivery time, only two transmissions are needed in the first RTT, leading to $RTO_1 = 600$ sec given that the length of RTT is 1200 sec. This leads to the maximum of the normalized goodput, which is completely consistent with the variation trend in Figure 6.

As we can see from Figure 5, it is obvious that the shorter the bundle, the better the normalized goodput performance for its RTO optimal and most other RTO_1 timer intervals. Figure 6 shows that along with the variations of the RTO_1 timer interval, the normalized goodput for a large bundle does not vary as significantly as for a small bundle. The performance variation indicates that the normalized goodput performance is significantly different when the bundle is larger than when the bundle is smaller. This is because the larger the bundle, the higher the likelihood of a corruption event for the larger RTO_1 timer intervals at a given BER. As a result, more bundles are retransmitted, and thus, more retransmission cycles required. As a result, the goodput performance degrades.

Figure 7 presents the normalized goodput performance of BP in transmission of a 10-Mbyte file with a BER of 5×10^{-6} and variations of bundle size. It is observed that under the same configuration, the larger the bundle size, the lower the normalized goodput performance. This is reasonable. Given a transmission channel condition, it is true that a larger bundle generally experiences the greater loss probability. With a higher loss rate for a bundle, more retransmission attempts are needed to secure its successful delivery. As a result, the file delivery time and the total amount of data sent increase dramatically, leading to a decrease in normalized effective goodput and degradation of the transmission efficiency.

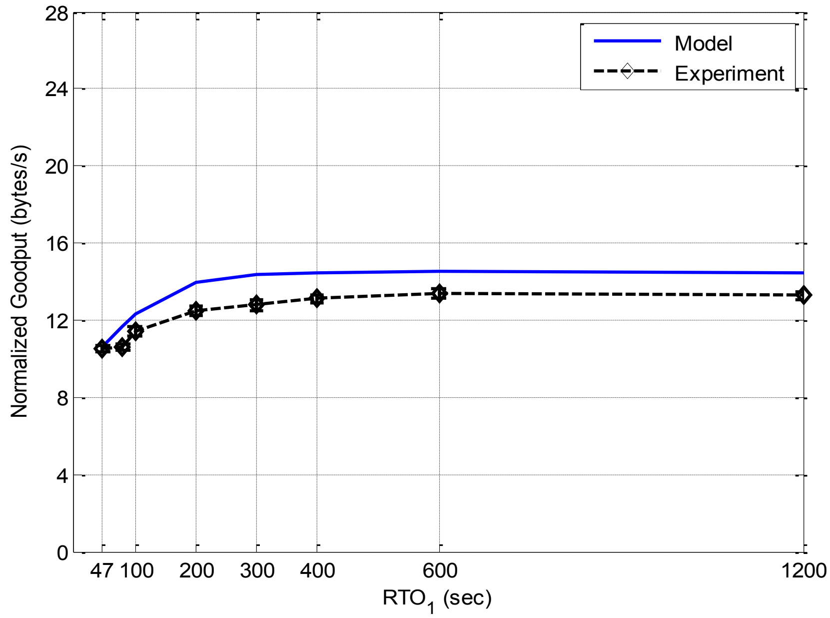

Fig. 6. Comparison of normalized goodput performance of BP with variations of RTO_1 timer interval, predicted by the model and observed in the experiments, in transmission of a 10-Mbyte file with a BER of 5×10^{-6} and a bundle size of 58 Kbytes.

6 Summary and Conclusions

In this paper, a reliable proactive retransmission mechanism is proposed for BP to ensure successful and reliable deep-space file transfer over unreliable space channels that likely cause unpredictable burst data losses due mainly to random link disruption events. The novelty of the approach is to use a hybrid of the *proactive retransmission* and *active retransmission*, with each employing different time intervals for the bundle's custodial RTO timer during file transfer. The model is validated by realistic file transfer experiments over a testbed infrastructure.

It is found that the optimal RTO timer intervals for custodial retransmission to achieve the highest normalized goodput performance are different depending on the bundle size and transmission conditions. For transmission over a lossy channel with a small bundle size (e.g., 30 Kbytes in our study), the optimal interval is very short, around 75 sec. With a large bundle size (e.g., around 60 Kbytes in our study), the optimal interval is much large (600 sec), around a half of the RTT length. According to our study, with a small bundle size, a small the RTO timer interval results in as many transmissions attempts as possible during the proactive retransmission phase (within the first RTT) so that the file delivery time can be minimized which leads to the highest normalized goodput. With a large bundle size over a lossy channel, it is found that the total data load over the channel has the greatest impact on the normalized goodput, and therefore, as many transmission attempts as possible should be made during the reactive retransmission phase (beyond the first RTT interval) so that the total data load can be minimized. This implies that the optimal interval of the RTO timer should be much larger in comparison to a small bundle size.

It is also found that over a lossy deep-space channel, the larger the bundle size is configured, the lower the normalized goodput performance is. This is reasonable because for transmission with a large bundle over a lossy channel, more retransmission attempts are needed to secure successful delivery of a file, leading to a longer file delivery time and thus decrease in normalized goodput.

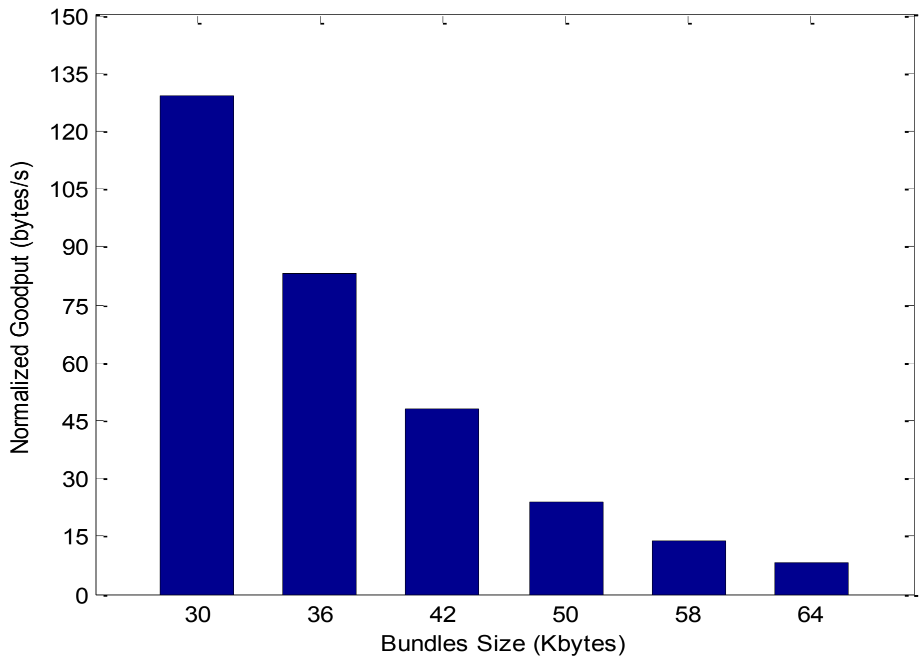

Fig. 7. Normalized goodput performance of BP in transmission of a 10-Mbyte file with a BER of 5×10^{-6} and variations of bundle size.

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