Reliable Proactive Retransmission of Bundle Protocol for Deep-Space Communications in Presence of Link Disruption

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***Abstract*—Reliable data transmission mechanisms of bundle protocol (BP) are presently under development for delay/disruption-tolerant networking (DTN). In this paper, a new transmission approach is proposed for BP for highly reliable data delivery in deep-space communications in presence of unpredictable or random link disruption. The main idea of the proposed approach is to employ a joint use of the proactive retransmission mechanism and active retransmission mechanism during file transfer. The performance of the approach is analyzed in four different cases according to different starting times of link disruption. Analytical models are built to estimate the effect of link disruption on BP transmission with focus on the number of transmission attempts and the total file delivery time affected by the link disruption. The models are validated by the file transfer experiment over a PC-based testbed.**

***Index Terms*—satellite communications, space communications, deep-space communications, space networks**

I. Introduction

As the main protocol of delay/disruption-tolerant networking (DTN) [1] for space, bundle protocol (BP) [2] is designed to establish an overlay network for reliable file transfer across heterogeneous communication networks. In [3], a general DTN architecture and protocol stacks are presented for a typical application example of BP in interoperating highly heterogeneous networks. As the DTN's main data transport protocol in space, Licklider transmission protocol (LTP) [4, 5] is developed for reliable data delivery in the presence of link disruption events and extremely long latency.

While DTN has been recognized as the only candidate networking technology that approaches the level of maturity required in deep-space communications [6], reliable transmission mechanisms for BP are presently under development. A series of studies [3, 7-14] have recently been done in protocol analysis and evaluation for space communications, with a focus on DTN-based space and deep-space networks. Some of these studies [7-8] focus on DTN's primary convergence layer (CL) protocols such as LTPCL while others [3, 9-14] focus on BP. In [14], a "proactive" retransmission mechanism is proposed for BP for reliable 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.

This approach 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 that lead to burst data losses. In case of a presence of a link disruption which cause unavailability of data link, 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.

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 that lead to burst data losses. The main idea of this proposed approach is to employ a joint use of the proactive retransmission and active retransmission during file transfer. Each of these two retransmission mechanisms uses different intervals for the bundle's custodial retransmission timeout (RTO) timer.

In [15], the proposed approach is studied in both analytical and experimental manners. However, it is studied with the effect of link disruption absolutely ignored. Therefore, the effectiveness of the approach in withstanding a link disruption event could not be evaluated in [15]. In this paper, the proposed approach is studied for reliable file delivery in presence of a link disruption whose length is shorter than the length of the communication round-trip time (RTT). The type of link disruption events is common in deep space. Analytical modeling is built for transmission effectiveness of the approach, focusing on the number of transmission attempts and the file delivery time affected by the link disruption. The models are validated by the file transfer experiment over a testbed.

II. Illustration of The Proposed Reliable Proactive Retransmission Mechanism of BP

Fig. 1 illustrates a file transmission scenario using the proposed reliable retransmission approach of BP. The proposed reliable proactive retransmission approach adopts a joint use of the proactive retransmission mechanism and reactive retransmission mechanism. As observed, 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. The objective of the proactive retransmission

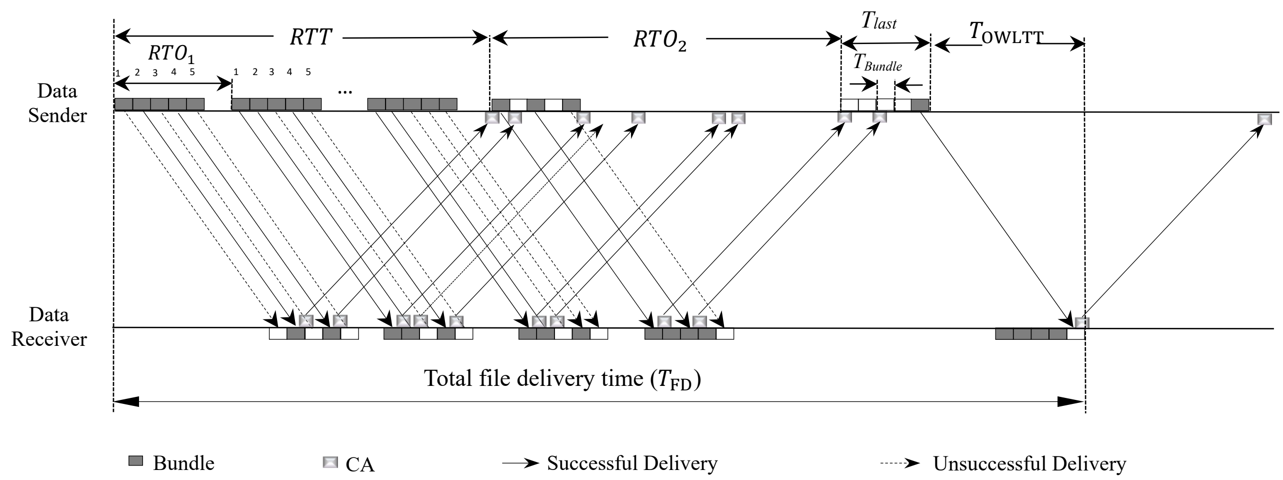

Fig.1. Illustration of a file transmission scenario using the proposed reliable proactive retransmission approach of BP which adopts a joint use of the proactive retransmission mechanism and reactive retransmission mechanism.

is to ensure highly reliable deep-space file transfer within a single communication round-trip interval. For the proactive retransmissions of the file done as the first phase of operation, 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. The operation is actually the same as the retransmission process done within the interval of RTT illustrated in [14].

The supplemental reactive retransmission process implemented as the operation in the second phase is intended to have additional transmission reliability in case the transmission attempts made in the first phase are not successful due to the unpredictable link disruption events or any other reason. It retransmits the data bundles based on the received acknowledgments or upon expiration of RTO timer. Therefore, the length of the RTO timer is generally configured to be slightly longer than the length of *RTT*. To differentiate it from the RTO timer length during the proactive retransmission phase, this timer for the reactive retransmission process 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.

III. Analytical Modeling of the Effect of Link Disruption

With respect to the end-to-end operation of the proposed retransmission approach illustrated in Fig. 1, assume that k transmission attempts are made during the first-phase proactive retransmission, and it satisfies $k = \left\lceil \frac{RTT}{RTO_1} \right\rceil$. Further assume the number of transmission attempts made beyond the first RTT is m. Then, the total number of transmission attempts is n that satisfies $n = k + m$.

The average number of the total transmission attempts to be carried out by the sender, n, was derived according to the channel transmission conditions in [15]. It is reiterated below

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

in which P_{Round} is the probability that a bundle is successfully delivered and its corresponding custody acknowledgment (CA) is successfully received. P_{Round} was formulated in [15]. The N_B in (1) is the number of data bundles that convey the entire file.

Let T_B be the bundle transmission time and T_{Prop} be the one-way propagation time of the deep-space link, then $T_B + T_{Prop}$ sis the total time length needed for the bundle to be successfully delivered at the receiver. Similarly, the total time elapsed for each transmission round after the first RTT period can be approximated as $T_B + RTO_2$. In the previous work [15], the file delivery time using the proposed proactive retransmission approach for file delivery *without link disruption event* involved was approximated as

$$\begin{aligned} T_{FD} = RTT + (m-1) \times (RTO_2 + T_B) \\ + T_{Prop} + T_{last} \end{aligned} \tag{2}$$

in which RTT is RTT length for the end-to-end file delivery and T_B is bundle transmission time which is determined by the data channel rate and the length of a bundle. The last time component, T_{last}, is an approximation of the transmission time for the last transmission attempt as illustrated in Fig. 1. Then, T_{last} can be formulated as $\frac{1}{N_B} \times \sum_{i=1}^{n} (i \times T_B)$ if the effect of delayed delivery of CAs in the asymmetric channel scenario is ignored.

Let T_{total} be the total file delivery time taken for successful file delivery using the proposed approach with link disruption event involved, and $T_{Break-Effect}$ be the effect of link disruption on file delivery time. With the baseline file delivery time T_{FD} derived in (2), T_{total} can be simply formulated as

$$T_{total} = T_{FD} + T_{Break-Effect} \tag{3}$$

In this paper, analytical performance models are built for estimating the effect of link disruption on BP transmission with

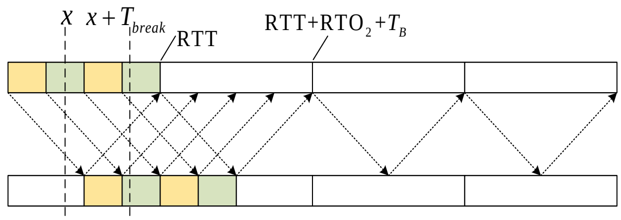

Fig. 2. A transmission scenario in presence of link disruption in Case A (i.e.,with x_a) —link disruption starts prior to the completeness of the first transmission attempts of the file.

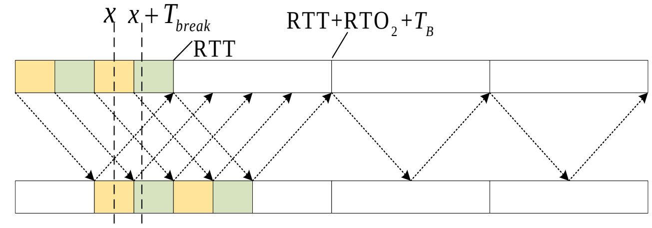

Fig. 3. A transmission scenario in presence of link disruption in Case B (i.e.,with x_b) —link disruption starts prior to the completeness of the first transmission attempts of the file.

focus on the total number of transmission efforts and the total file delivery time taken for successful bundle delivery. Let x be the disruption starting time and T_{break} be the link disruption duration. As mentioned, this study focuses on the effect of a short link disruption, and the disruption duration is shorter than the length of RTT, i.e., $T_{break} < RTT$.

In real deep-space flight missions, the link disruption events can occur randomly at any time during file transfer for different reasons. Therefore, different starting times of the link disruptions are considered in this study. The starting time is divided into four different ranges that are labelled as x_a, x_b, x_c and x_d in Fig. 1. The performance analysis of the proposed reliable proactive retransmission approach is divided into four different cases according to these four starting times.

Case A (i.e., with x_a): $x < T_B + T_{prop}$ and $x + T_{break} \leq RTT$

Case A (i.e., with x_a) is the transmission case in which link disruption starts prior to the completeness of the first transmission attempts of the file. In other words, the link disruption starts before the first bundle transmission time and propagation time is over. Let x be the starting time of link disruption. It can be formulated as $x < T_B + T_{prop}$ in this case. With a short disruption (i.e., $T_{break} < RTT$), it is true that $x + T_{break} \leq RTT$. A general transmission scenario in this case is illustrated in Fig. 2.

It is observed that no bundle is successfully delivered to the data receiver before the link disruption starts. Furthermore, the formula of $x + T_{break} \leq RTT$ means that the disruption ends within the interval of the first RTT. The transmission attempts affected by the disruption can only be retransmitted after the event is over. Let N_{break} be the number of transmission attempts affected by the link disruption and failed for delivery. As the retransmissions during the link disruption follows the length of RTO_1, N_{break}, can be formulated as

$$N_{break} = \left\lceil \frac{x + T_{break}}{RTO_1} \right\rceil \tag{4}$$

In a deep-space communications system with high bit-error-rate, the required number of retransmissions will increase. The numerical value of N_{break} is a part of k which is the configured number of transmission attempts made during the first-phase proactive retransmission. According to $n = k + m$, k is a part of the total number of transmission attempts required for successful delivery of the file. Therefore, the number of transmission attempts affected by the link disruption N_{break} need to be retransmitted (after the RTT interval) during the reactive retransmission phase with a retransmission interval of RTO_2, as illustrated in Fig. 2. As the total time elapsed for each transmission round after the first RTT period is approximated as $(T_B + RTO_2)$, the effect of link disruption on file delivery time $T_{Break-Effect}$ can be written as $N_{break} \times (T_B + RTO_2)$.

Based on the above analysis, with the baseline file delivery time (without link disruption involved), T_{FD}, derived in (2) and the formula for T_{total} presented in (3), the total file delivery time with the effect of link disruption included can be formulated as

$$\begin{aligned} T_{total} &= T_{FD} + T_{Break-Effect} \\ &= RTT + (m-1) \times (RTO_2 + T_B) + T_{Prop} + T_{last} \\ &\quad + N_{break} \times (T_B + RTO_2) \\ &= RTT + \left(m + \left\lceil \frac{x + T_{break}}{RTO_1} \right\rceil - 1\right) \times (T_B + RTO_2) \\ &\quad + T_{prop} + T_{last} \end{aligned} \tag{5}$$

Case B (i.e., with x_b): $T_B + T_{prop} \leq x < RTT$ and $x + T_{break} \leq RTT$

Case B (i.e., with x_b) is the transmission case in which link disruption starts after the first transmission attempt completes (arrives at the receiver) but before the RTT ends, i.e., $x \geq T_B + T_{prop}$, as illustrated in Fig. 3. Therefore, the bundles of the file arrive at the receiver at least once before the disruption starts.

Similar to Case A, the link disruption only affects transmissions within the first RTT interval. The number of transmission attempts made before the link disruption starts is $\left\lceil \frac{x - T_{prop}}{RTO_1} \right\rceil$, and the total number of transmission attempts made up to the end of link disruption is $\left\lceil \frac{x + T_{break}}{RTO_1} \right\rceil$. Therefore, in this case, N_{break} can be formulated as

$$N_{break} = \left\lceil \frac{x + T_{break}}{RTO_1} \right\rceil - \left\lceil \frac{x - T_{prop}}{RTO_1} \right\rceil \tag{6}$$

Accordingly, similar to the analysis of Case A, according to (3), T_{total} can be rewritten as

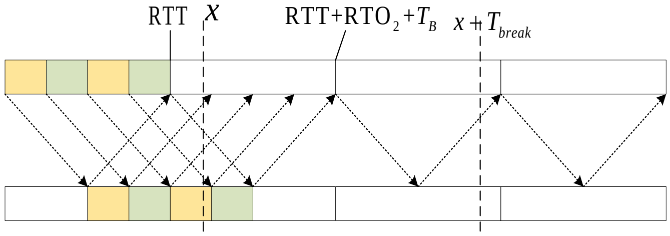

Fig. 4. A transmission scenario in presence of link disruption in Case C (i. e., with x_c) —link disruption starts after the RTT length but before the first RTO_2 timer expires.

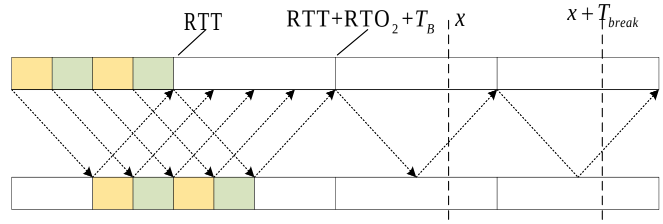

Fig. 5. A transmission scenario in presence of link disruption in Case D (i. e., with x_d) —link disruption starts after the first RTO_2 timer expires.

$$T_{total} = RTT + \left(m + \left\lceil \frac{x + T_{break}}{RTO_1} \right\rceil - \left\lceil \frac{x - T_{prop}}{RTO_1} \right\rceil - 1\right) \times (T_B + RTO_2) + T_{prop} + T_{last} \quad (7)$$

Case C (i. e., with x_c) : $RTT \le x < RTT + (RTO_2 + T_B)$

In Case C (i. e., with x_c), it is assumed that the link disruption starts after the RTT length but prior to expiration of the first RTO_2 timer. A general transmission scenario in this case is illustrated in Fig. 4. As shown, more than half of transmission attempts made within a single RTT are completed before the disruption starts. However, there may still be some transmissions that cannot be completed within a single RTT, depending on whether the number of transmissions in a single RTT interval are completed prior to the interruption starting time.

As discussed, there are k transmission attempts made within the first RTT interval. Since the $(k+1)th$ transmission attempt is not performed immediately after a single RTT, the disruption starting time x may fall into a time range of $RTT \sim k \times RTO_1$. Since the time interval of $(k \times RTO_1 - RTT)$ is too short, there is no significance to discuss this time range. Therefore, we only consider the situation in which the range of the disruption starting times satisfies $k \times RTO_1 \le x < (RTT + RTO_2)$.

Let c be a variable factor to determine whether the transmission attempt made at the disruption starting time is successful, and it is defined as

$$c = \left\lfloor \frac{x}{k \times RTO_1 + T_B + T_{prop}} \right\rfloor \quad (8)$$

The bundle delivery in this round is not affected by the disruption if $\left(k \times RTO_1 + T_B + T_{prop}\right) \le x < RTT + RTO_2 + T_B$), that is $c = 1$. Otherwise, $c = 0$, which means that the data link resources taken by this transmission attempt affected by the disruption is wasted. Then, the number of successful transmission attempts made within the first RTT interval can be written as $\left(\left\lceil \frac{x - T_{prop}}{RTO_1} \right\rceil - c \times \left\lceil \frac{x - T_{prop} - RTT}{RTO_1} \right\rceil\right)$. Furthermore, the number of transmission attempts affected by the link disruption within the first RTT intervsal can be defined as

$$N_{break\_bef} = k - \left(\left\lceil \frac{x - T_{prop}}{RTO_1} \right\rceil - c \times \left\lceil \frac{x - T_{prop} - RTT}{RTO_1} \right\rceil\right) \quad (9)$$

The number of transmissions affected by interruption beyond the first RTT can be written as

$$N_{break\_aft} = \left\lceil \frac{x + T_{break} - k \times RTO_1}{T_B + RTO_2} \right\rceil - \left\lfloor \frac{x - k \times RTO_1}{T_B + RTO_2} \right\rfloor - c \quad (10)$$

Accordingly, the total number of transmission attempts affected by the link disruption N_{break}, can be formulated as

$$N_{break} = N_{break\_bef} + N_{break\_aft} = k - \left(\left\lceil \frac{x - T_{prop}}{RTO_1} \right\rceil - c \times \left\lceil \frac{x - T_{prop} - RTT}{RTO_1} \right\rceil\right) + \left\lceil \frac{x + T_{break} - k \times RTO_1}{T_B + RTO_2} \right\rceil - \left\lfloor \frac{x - k \times RTO_1}{T_B + RTO_2} \right\rfloor - c \quad (11)$$

With N_{break} derived, T_{total} in this case can be rewritten as

$$T_{total} = RTT + \left(m + k - \left(\left\lceil \frac{x - T_{prop}}{RTO_1} \right\rceil - c \times \left\lceil \frac{x - T_{prop} - RTT}{RTO_1} \right\rceil\right) + \left\lceil \frac{x + T_{break} - k \times RTO_1}{T_B + RTO_2} \right\rceil - \left\lfloor \frac{x - k \times RTO_1}{T_B + RTO_2} \right\rfloor - c - 1\right) \times (T_B + RTO_2) + T_{prop} + T_{last} \quad (12)$$

Case D (i. e., with x_d) : $x > RTT + RTO_2 + T_B$

Case D (i. e., with x_d) is the transmission case in which link disruption starts after the first RTO_2 timer expires. A general transmission scenario in this case is illustrated in Fig. 5. Because x is greater than $(RTT + RTO_2 + T_B)$, only the transmission after a single RTT time is affected by the link disruption. Let d as a variable factor to determine whether the transmission attempt at the disruption starting time is successful, and it is defined as

$$d = \left\lfloor \frac{x - k \times RTO_1}{\left\lfloor \frac{x - k \times RTO_1}{T_B + RTO_2} \right\rfloor \times (T_B + RTO_2) + T_B + T_{prop}} \right\rfloor \quad (13)$$

The role of d in this case is similar to the role of c in Case C. In other words, $d = 1$ indicates the bundle delivery in this round is not affected by the disruption while $d = 0$ means that the bundle delivery in this round is affected. Therefore, N_{break} in this case can be formulated as

$$N_{break} = \left\lceil \frac{x + T_{break} - k \times RTO_1}{T_B + RTO_2} \right\rceil - \left\lfloor \frac{x - k \times RTO_1}{T_B + RTO_2} \right\rfloor - d \quad (14)$$

According to N_{break} in (14), T_{total} in this case can be rewritten as

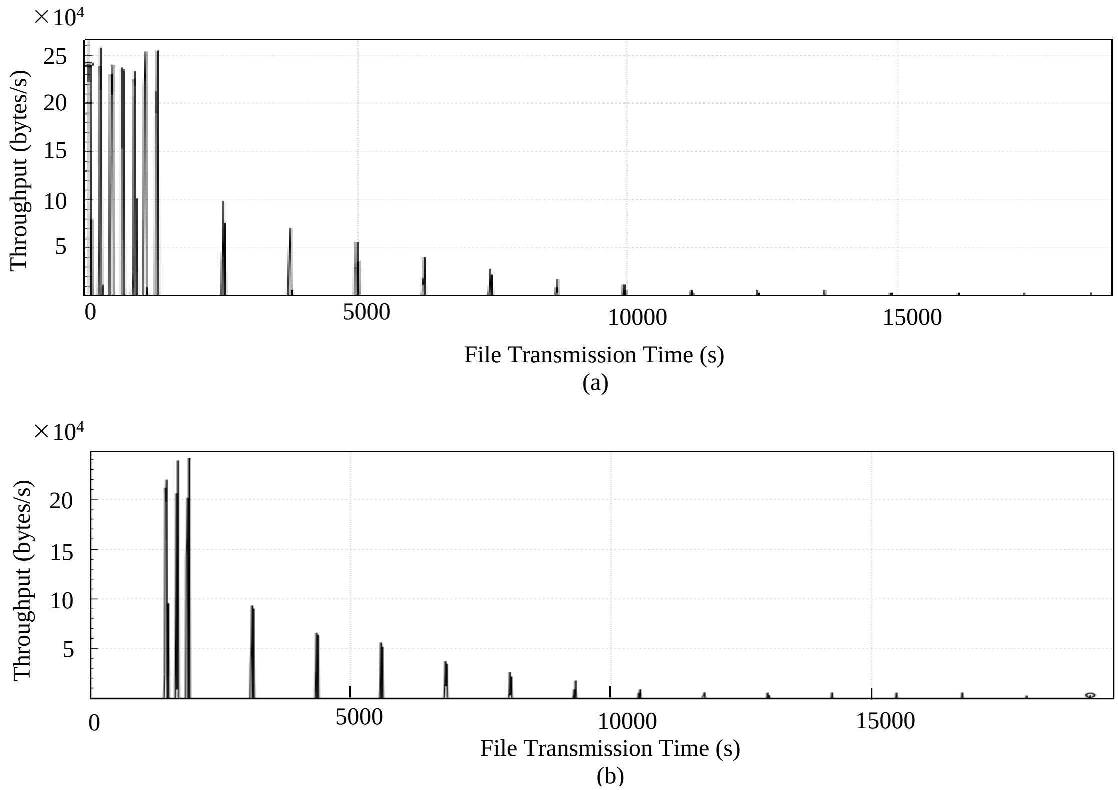

Fig.6. Throughput traces of the proposed retransmission approach of BP in transmission of a 10 Mbytes file over deep-space channel with a one-way link delay of 10 minutes at the bundle size of 30 Kbytes in presence of link disruption in Case A (with $x = 300$ sec and $T_{break} = 400$ sec) and with the RTO_1 length of 207 sec and RTO_2 length of 1240 sec. (a) At sender. (b) At receiver.

$$T_{total} = RTT + \left(m + \left\lceil \frac{x + T_{break} - k \times RTO_1}{T_B + RTO_2} \right\rceil - \left\lfloor \frac{x - k \times RTO_1}{T_B + RTO_2} \right\rfloor - d - 1\right) \times (T_B + RTO_2) + T_{prop} + T_{last} \quad (15)$$

IV. SAMPLES OF EXPERIMENTAL RESULTS AND MODEL VALIDATION

The file transfer experiments are conducted over the testbed to validate the analytical models. The experimental infrastructure is the PC-based space communication and networking testbed (SCNT) [7] emulating a deep-space communication scenario. The infrastructure was validated through a series of our previous studies [7-14]. The implementation of BP was adapted from the Interplanetary Overlay Network (ION) [16] distribution v3.6.2 with the proposed reliable retransmission mechanism implemented.

All four file transmission cases analyzed in Section III are experimented by transmitting a 10-Mbyte file from the sender to the receiver using BP running the proposed transmission approach with one-way link delay of 10 minutes. The one-way delay of 600 sec is common over a deep-space channel, leading to a length of RTT approximately around 1200 sec. Other transmission conditions include a BER of 5×10^{-6}, asymmetric channel ratio of 300/1 (2 Mbits/s vs 6.7 Kbits/s) and a bundle length of 30 Kbytes. The lengths of RTO_1 and RTO_2 are configured to be 207 sec and 1240 sec, respectively.

Fig. 6 illustrates the throughput traces of the proposed retransmission approach of BP in transmission of a 10 Mbytes file in presence of link disruption in Case A (with $x = 300$ sec and $T_{break} = 400$ sec) at both the sender and the receiver. The traces show individual throughput spikes at both nodes as a result of the individual transmission attempts over the channel. It is observed that the data receiver does not receive the data bundles from the sender until the inevitable one-way propagation time of 10 min passes after the link recovery.

In a comparison of the throughput traces between two nodes, four throughput spikes are missing at the receiver. This is an indication that their corresponding four transmission attempts are failed because of the link disruption experienced by the file transmission. With $x = 300$ sec, $T_{break} = 400$ sec and other configured experimental parameters plugged (4), the numerical value of N_{break} is also four which is the same as experimental result measured during file transfer. Similarly, the total file delivery time observed from the traces in Fig. 6 is approximately 19218 sec, which is roughly equal to T_{total} calculated by formula (5). Accordingly, the average throughput obtained by the experiment is 520.35 bytes/sec.

Similarly, Fig. 7 illustrates the throughput trace of the proposed retransmission approach of BP in presence of link disruption in Case B (with $x = 700$ sec and $T_{break} = 200$ sec) measured at the receiver. The trace measured at the sender is almost the same as the one in Case A (i.e., Fig. 6(a)), and therefore, it is not shown in Fig. 7. It is observed that unlike in Case A, the data receiver receives data bundles sent by the

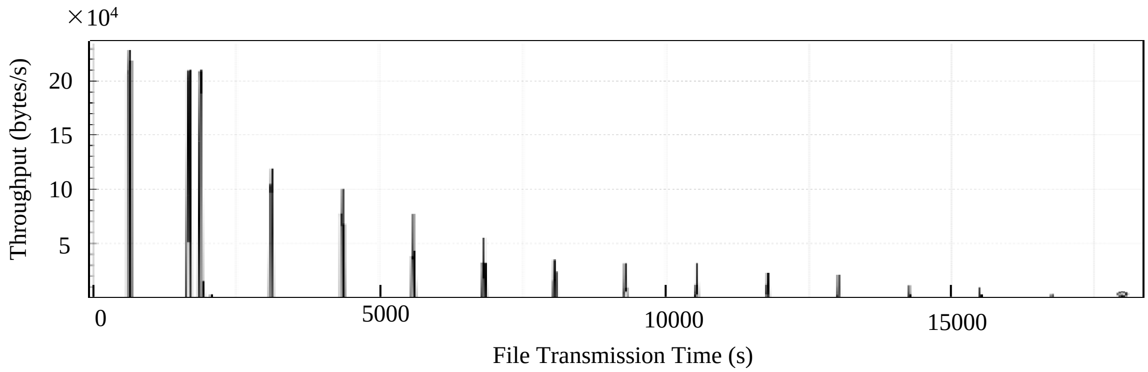

Fig.7. Throughput trace of the proposed retransmission approach of BP in presence of link disruption in Case B (with $x = 700$ sec and $T_{break} = 200$ sec) measured at the receiver with all other conditions configured the same as in Fig. 6.

sender for the first attempt. It can be seen from Fig. 7 that the number of transmission attempts shown at the receiver is 16. Obviously, four transmission attempts are affected by the link disruption in this case and they fail to arrive at the receiver. It is also observed that the file delivery time is approximately 17997 sec which is same as the file delivery time calculated by (7). In addition, the average throughput obtained by the experiment is 555.65 bytes/sec.

The average throughput, 520~560 bytes/sec, in both cases is considered low because of the extremely long total file delivery time. The extremely long file delivery time is caused by the combined effect of very long one-way propagation delay of 600 sec and failure of many transmission attempts and retransmissions.

V. SUMMARY AND CONCLUSIONS

In this paper, a reliable proactive retransmission mechanism is proposed for DTN's BP for highly reliable data delivery in presence of unpredictable or random link disruption in deep-space communications. The proposed approach employs a joint use of the proactive retransmission mechanism and active retransmission mechanism during file transfer. 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.

The performance of the proposed approach is analyzed in four different cases of BP according to different starting times of link disruption event. Analytical models are built for estimating the effect of link disruption on BP transmission with focus on the number of transmission attempts and the total file delivery time taken for successful file delivery. The models are validated by the end-to-end bundle delivery experiments over a testbed. It is found that the models predict both the additional number of transmission efforts caused by the link disruption and the total file delivery time for successful file delivery.

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