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Research paper

Modeling the RTT of bundle protocol over asymmetric deep-space channels

BIAN Zhengguo, ZHANG Gengxin, BIAN Dongming

College of Communication Engineering, PLA University of Science and Technology, Nanjing 210007, China

Abstract: Delay/disruption-tolerant networking communications rely heavily on BP (Bundle Protocol), which uses the well-known approach of store-and-forward with optional custody transfer to deal with stressed communication environments. The use of BP and its performance in deep-space communication has been the subject of debate. The accurate estimate of file delivery latency (i.e., RTT (Round Trip Time)) is essential for efficient transmission control, reliable delivery, and bandwidth usage optimization of a protocol. In this paper, we present a performance analysis of BP running over UDPCL/UDP over deep-space channels, focusing on the RTT estimate, in the presence of highly asymmetric channel rates. Analytical models are built for the RTT estimate of the BP/UDPCL transmissions considering the effect of delay caused by space channel-rate asymmetry, and, channel impairment. The models are validated by file transfer experiments using a PC-based testbed. It is found that a smaller bundle size (if smaller than a calculated threshold) results in a longer delay in custody acknowledgment transmission, and thus, a longer RTT.

Key words: deep-space communications, delay/disruption-tolerant networking, bundle protocol

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1 Introduction

As is well-known, the existing TCP/IP (Transmission Control Protocol/Internet Protocol) is ineffective in challenging space communication which are characterized by long and variable signal propagation delays, intermittent connectivity, heavy channel noise, and asymmetric data link rates, especially in deep-space[1]. DTN (Delay/disruption-tolerant networking) is an overlay-network technology designed for communications in or through highly stressed environments. DTN is presently recognized as the only candidate architecture that approaches the level of maturity required to handle the inevitable long delays and unpredictable link disconnection inherent in deep-space communications[2]. DTN communications rely heavily on a BP (Bundle Protocol)[3], which uses the well-known approach of store-and-forward with optional custody transfer to deal with challenging environments[4,5]. The optional custody transfer, once enabled, allows certain DTN nodes to operate as custodial nodes, responsible for guaranteeing the reliable data forwarding towards the next hop. These mechanisms ensure that no data

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packets are lost, even if a router is temporarily out of sight because of occultation or rotation in deep space.

In addition to the lengthy signal propagation delay and link disruption that are commonly known in space communications, deep-space links are characterized by highly asymmetric channel rates: the uplink channel rate for ACK (Acknowledgment) transmission from the Earth to the Mars orbiter in deep space is generally much lower than the downlink channel rate for data transmission from the Mars orbiter to the Earth[6,7]. When the channels are highly asymmetric, the low-rate forward channel is too slow to handle the transmission of returning CAs (Custody Acknowledgements) effectively, resulting in significant CA delay, which delays the transmission of new data packets and thus reduces goodput performance.

The performance modeling RTT (Round Trip Time) of Licklider transmission protocol[8] for reliable data delivery over asymmetric deep-space communications has previously been studied by file transfer emulation experiments. However, little work has been seen on performance modeling the RTT of BP in space communication systems. Therefore, in this paper,

we model the performance of BP file transmission in the presence of the extremely long signal propagation delay and highly asymmetric channel rates that characterize deep-space communication. Analytical models are built to estimate the RTT of BP transmissions considering the effect of delay caused by channel-rate asymmetry. The models are validated by running file transfer experiments using a testbed.

2 Modeling effect of custody acknowledgment delay on BP/UDPCL transmissions

As discussed, a very low ACK channel rate will cause the delay of CA transmission, which then increases the RTT for bundle transmission, eventually leading to goodput performance degradation. Therefore, in order to quantize the effect of CA delay on the RTT for bundle transmission over an asymmetric channel, we built an analytical model to characterize the variation of RTT with respect to the length of a bundle.

If we define T_{bundle} to be the average bundle transmission time and T_{ca} to be the average CA transmission time, then

$$T_{\text{bundle}} = \frac{L_{\text{bundle}} + L_{\text{bundle\_head}}}{R_{\text{data}}} \text{ and } T_{\text{ca}} = \frac{L_{\text{ca}}}{R_{\text{ca}}}, \tag{1}$$

where L_{bundle} is the average length of the bundle that needs to be acknowledged entirely by the receiver, $L_{\text{bundle\_Head}}$ is the length of the bundle header, R_{data} is data channel rate, L_{ca} is the average length of a CA, and R_{ca} is the ACK channel rate.

The average time that a CA will wait for the previous CA transmission to complete after it is generated for transmission is defined as

$$T_{\text{ca-wait}} = T_{\text{ca}} - T_{\text{bundle}}. \tag{2}$$

Obviously, CA waiting time, $T_{\text{ca-wait}}$, contributes to the length of the RTT. To explain the magnitude of $T_{\text{ca-wait}}$ caused by highly asymmetric channel rates, Fig.1 illustrates a scenario of the bundle and CA interactions for BP when an entire file is transmitted between the sender and receiver. In this scenario, a file consists of ten bundles defined as the first to the tenth, and they are transmitted continuously in the first transmission effort. However, because of the presence of channel noise, two out of ten bundles (the fifth and ninth) are lost and cannot be delivered to the receiver. Upon arrival of the rest of the eight bundles, the receiver sends a CA in response to each of them following the "one CA per bundle" policy. Then, a CA for the fourth bundle is lost over the ACK channel. This could occur if the sender releases the region of memory occupied by the corresponding bundle as soon as a CA (for the next seven bundles) is received. Then the sender resends the bundle if its

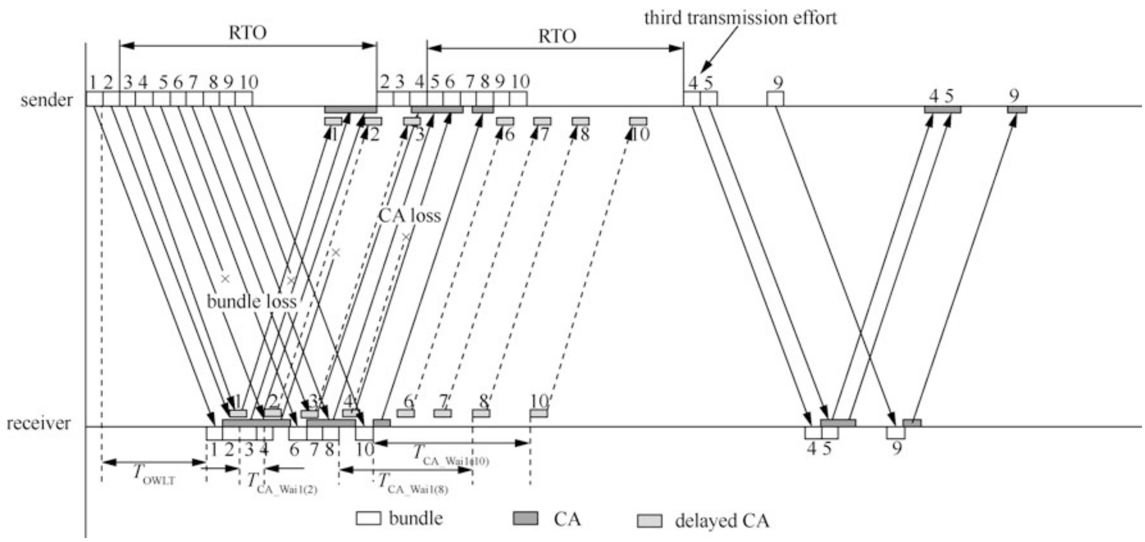

Figure 1 BP bundles transmission and interactions between sender and receiver

corresponding CA has not been received (because of the loss of a bundle or CA) by the time the bundle's RTO (Retransmission TimeOut) timer expires in the second transmission effort.

However, the CAs for the eight bundles in the receiver node will be delayed because of the very slow ACK channel rate. As illustrated in Fig.1, a delay in CA transmission (i.e., $T_{\text{ca-wait}}$) is experienced for all of the seven CAs except the first one. In addition we also find that the value of $T_{\text{ca-wait}}$ increases with the sequence of the CAs. That is, the CA waitingtime in the receiver node is cumulative for consecutively transmitted bundles. Therefore, for the transmission of a file in a large number of data bundles, $T_{\text{ca-wait}}$ significantly increases the RTT of those bundles over time, and this severely degrades transmission performance. To eliminate this effect, it is required that $T_{\text{ack-wait}} \leqslant 0$, i.e.,

$$T_{\text{bundle}} \geqslant T_{\text{ca}} \,. \tag{3}$$

Given the formulas for T_{bundle} and T_{ca} in Eqs.(1) and (3), $T_{\text{ca-wait}}$ can be rewritten as

$$L_{\text{bundle}} \geqslant \frac{L_{\text{ca}} \cdot R_{\text{data}}}{R_{\text{ca}}} - L_{\text{bundle\_head}} \,. \tag{4}$$

The above derivation states that Eq.(4) must be maintained in order to avoid CA transmission delay. In other words, $\frac{L_{\text{ca}} \cdot R_{\text{data}}}{R_{\text{ca}}} - L_{\text{bundle\_head}}$ is actually the minimum average length of the application data portion encapsulated within a bundle (which can be defined as $L_{\text{bundle-min}}$) that should be acknowledged entirely by the receiver to avoid CA transmission delay, i.e.,

$$L_{\text{bundle-min}} = \frac{L_{\text{ca}} \cdot R_{\text{data}}}{R_{\text{ca}}} - L_{\text{bundle\_head}} \,. \tag{5}$$

Case I: $L_{\text{bundle}} \geqslant L_{\text{bundle-min}}$. As is well known, the RTT is defined as the time the data bundle is sent to when its acknowledgement is received (i.e., the CA information), generally including the transmission time, propagation time, processing time, and queue time.

In the case where the length of the bundle is greater than or equal to $L_{\text{bundle-min}}$, the delay for CA transmission could be avoided. Therefore, the RTT for a bundle transmission can be roughly described (if the processing delay and queue delay are ignored) as

$$RTT = 2T_{\text{owlt}} + T_{\text{bundle}} + T_{\text{ca}} \,, \tag{6}$$

where T_{owlt} represents the one-way-light-time (i.e., OWLT (one way propagation delay)) from the Mars orbiter (i.e., data sender) to the Earth ground station (i.e., data destination) as illustrated in Fig.1.

The protocol processing delay and queue delay for data bundle transmission are ignored in Eq.(6). This is reasonable. Given that round-trip light time approaches 600 s over a long-haul Mars to Earth channel (as investigated in this work), the processing delay and queue delay is significantly shorter in comparison to the extremely long round-trip propagation delay in deep space.

Therefore, plugging Eq.(1) into Eq.(6), the RTT for a bundle transmission can be written as

$$\begin{aligned} RTT &= 2T_{\text{owlt}} + T_{\text{bundle}} + T_{\text{ca}} \\ &= 2T_{\text{owlt}} + \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}} + \frac{L_{\text{ca}}}{R_{\text{ca}}}. \end{aligned} \tag{7}$$

Case II: $L_{\text{bundle}} < L_{\text{bundle-min}}$. As discussed earlier, if the bundle size L_{bundle} is shorter than $L_{\text{bundle-min}}$, it results in a CA transmission delay. We denote that the RTT for the first bundle and CA transmission as RTT_1, similarly, the second and the nth bundle transmission are denoted as RTT_2 and RTT_n, respectively. Therefore, with the processing time and queue time ignored, as in Case I, the average RTT for the transmission of a total file in bundles can be computed as

$$RTT = \frac{RTT_1 + RTT_2 + \ldots + RTT_n}{n}, \tag{8}$$

where n is the total number of the CAs transmitted by the receiver. In addition n should be equal to the total number of the bundles included in a file for transmission by the sender following the "one CA per bundle" acknowledgement mechanism.

Following Eq.(8), we should compute the every RTT value in order to derive the value of the average RTT.

In the first transmission effort, assume that NB_{1_rx} bundles are successfully delivered to the receiver. Following the "one CA per bundle" acknowledgement mechanism, there should be around NB_{1_rx} CAs generated for transmission by the receiver. However, in Fig.1, we can see that all of the CA transmissions are seriously delayed because of the highly asymmetric channel rates, as a result, the CAs may arrive at the sender after the corresponding bundle timeout timers expire. In other words, all the bundles (except the first one) transmitted in the first transmission effort are retransmitted in the second transmission effort (as illustrated in Fig.1, in the second transmission effort, nine bundles excepting the first one are retransmitted). In this case, the receiver node would send NB_{1_rx} CAs to the sender node in the second transmission effort. After the sender receives NB_{1_rx} CAs, only a part of them are transmitted effectively.

In the third transmission effort, the sender will retransmit the bundles that were not released in the first and second transmission efforts, and then the receiver node sends NB_{3_rx} CAs to the sender node. After theoretical analysis, it shows that NB_{3_rx} CAs which are limited so that they do not cause delay. Hence, the CA transmission delay is avoided in the third and the later transmission efforts until the delivery of the entire file to its destination node is complete.

As described above, we can draw the conclusion that only those bundles that are transmitted to the receiver node successfully in the first and second transmission efforts will cause delay in the transmission of the corresponding CA information. The rest of the bundles that are transmitted successfully in the third and later transmission efforts could avoid CA transmission delay.

Therefore, in order to derive the RTT value for every bundle and its corresponding CA, on one hand, we need to compute the total number of bundles that are transmitted successfully in the first and second transmission efforts, and on the other hand, we need to compute the average RTT for bundle transmission with CA delay. We compute the two parts, respectively.

First, let the uncorrected BER (Bit-Error-Rate) of a deep-space channel be p. Provided that all bits are transmitted independently, the loss probability of a bundle can be formulated as follows.

$$p_{\text{bundle}} = 1-(1-p)^{8(L_{\text{bundle}}+L_{\text{bundle-head}})} .$$

Similarly, the loss probability of a CA can be formulated as

$$p_{\text{ca}} = 1-(1-p)^{8L_{\text{ca}}} .$$

Assume that an entire file is transmitted in n bundles, i.e., $n=L_{\text{file}}/L_{\text{bundle}}$. Therefore, in the first transmission effort, the number of bundles sent from the orbiter to the receiver node can be defined as NB_{1_mx}, i.e., $NB_{1\_\text{mx}}=n$.

Therefore, considering the loss of bundles and CAs (due to the presence of the channel error), for the first transmission effort, the number of bundles that are transmitted successfully, defined as NB1, can be formulated as

$$\begin{aligned} NB_1 &= NB_{1\_\text{mx}}(1-p_{\text{bundle}})(1-p_{\text{ca}}) \\ &= n(1-p_{\text{bundle}})(1-p_{\text{ca}}) \ . \end{aligned}$$

Accordingly, the number of bundles that are lost in the first transmission effort, defined as NB_{1_n}, can be written as

$$\begin{aligned} NB_{1\_n} &= NB_{1\_\text{mx}} - NB_1 \\ &= n[1-(1-p_{\text{bundle}})(1-p_{\text{ca}})] \ . \end{aligned}$$

As discussed, In the second transmission effort, the number of bundles that need to be retransmitted equals the number of bundles that are lost in the first transmission effort, i.e., $NB_{1\_\text{mx}=}NB_{1\_n}$, and it can be written as

$$NB_{2\_\text{mx}} = n[1-(1-p_{\text{bundle}})(1-p_{\text{ca}})] \ .$$

Similarly, in the second transmission effort, the number of bundles that are transmitted successfully, defined as NB_2, can be formulated as

$$\begin{aligned} NB_2 &= NB_{2\_\text{mx}}(1-p_{\text{bundle}})(1-p_{\text{ca}}) \\ &= n[1-(1-p_{\text{bundle}})(1-p_{\text{ca}})](1-p_{\text{bundle}})(1-p_{\text{ca}}). \end{aligned}$$

Therefore, the total number of bundles that are transmitted successfully in the first and second transmission efforts, defined as N_1, can be written as

$$\begin{aligned} N_1 &= NB_1 + NB_2 \\ &= n(1-p_{\text{bundle}})(1-p_{\text{ca}}) + n[1-(1-p_{\text{bundle}}) \\ &\quad \cdot (1-p_{\text{ca}})](1-p_{\text{bundle}})(1-p_{\text{ca}}) \\ &= n\left[2-(1-p_{\text{bundle}})(1-p_{\text{ca}})\right] \\ &\quad \cdot (1-p_{\text{bundle}})(1-p_{\text{ca}}) \\ &= \frac{L_{\text{file}}}{L_{\text{bundle}}}[2-(1-p_{\text{bundle}})(1-p_{\text{ca}})] \\ &\quad \cdot (1-p_{\text{bundle}})(1-p_{\text{ca}}) \ . \end{aligned} \tag{9}$$

Second, we need to compute the average RTT for the bundle transmission with the CA delay involved. We know that the bundles are transmitted continuously and the relative time between them is unchanged, including the retransmission scenarios, and each of them contains time stamp. Considering that the N_1 bundles in the first and second transmission efforts are random because of the randomness of bundles and CAs losses and they can be any of the n bundles involved in the source file, an average approach is taken to estimate the average RTT of these bundles.

From Eq.(2), we know that the average time the nth CA waits for transmission (or simply, the delay in the nth CA transmission) is $T_{\text{ca}}-T_{\text{bundle}}(n-1)$. In other words, the delay in CA transmission increases linearly according to an increase in the number of bundles requiring acknowledgment, i.e., the number of previously issued CAs that must be transmitted before this CA may be transmitted. Therefore, considering the nature of linear increase, the average delay in CA for transmission of the entire file can be approximated as

$$\begin{aligned} T_{\text{ca-delay}} &\approx \frac{1}{2}(T_{\text{ca}}-T_{\text{bundle}})(n-1) \\ &= \frac{1}{2}(T_{\text{ca}}-T_{\text{bundle}})\left(\frac{L_{\text{file}}}{L_{\text{bundle}}}-1\right) \ . \end{aligned}$$

Based on the above discussion, with the processing time and queue time ignored as in Case I, the average RTT for bundle transmission with CA delay, defined as RTT_{average}, can be derived as

$$RTT_{\text{average}} \approx 2T_{\text{owlt}} + T_{\text{bundle}} + T_{ca} + T_{\text{ca-delay}} = 2T_{\text{owlt}} + \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}} + \frac{L_{\text{ca}}}{R_{\text{ca}}} + \frac{1}{2} \cdot \left(\frac{L_{\text{ca}}}{R_{\text{ca}}} - \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}}\right)\left(\frac{L_{\text{file}}}{L_{\text{bundle}}} - 1\right). \tag{10}$$

Therefore, using the total number of bundles N_1 that are transmitted successfully in the first and second transmission efforts, (derived in Eq.(9)), RTT_{average}, the average RTT for bundle transmissions with CA delay , (derived in Eq.(10)), the total RTT value of N_1 bundles, defined as RTT_{n1_total}, can be formulated as

$$RTT_{n1\_\text{total}} = RTT_{\text{average}} N_1 = \left(2T_{\text{owlt}} + \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}} + \frac{L_{\text{ca}}}{R_{\text{ca}}} + \frac{1}{2} \cdot \left(\frac{L_{\text{ca}}}{R_{\text{ca}}} - \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}}\right)\left(\frac{L_{\text{file}}}{L_{\text{bundle}}} - 1\right)\right) \cdot \frac{L_{\text{file}}}{L_{\text{bundle}}}[2 - (1 - p_{\text{bundle}})(1 - p_{\text{ca}})] \cdot (1 - p_{\text{bundle}})(1 - p_{\text{ca}}). \tag{11}$$

As discussed above, the rest of the bundles that are transmitted successfully in the third and the later transmission efforts that could avoid CA transmission delay, defined as N_2, can be written as

$$N_2 = n - N_1 = \frac{L_{\text{file}}}{L_{\text{bundle}}} - \frac{L_{\text{file}}}{L_{\text{bundle}}}[2 - (1 - p_{\text{bundle}}) \cdot (1 - p_{\text{ca}})](1 - p_{\text{bundle}})(1 - p_{\text{ca}}) = \frac{L_{\text{file}}}{L_{\text{bundle}}}(1 - 2(1 - p_{\text{bundle}})(1 - p_{\text{ca}}) + [(1 - p_{\text{bundle}})(1 - p_{\text{ca}})]^2). \tag{12}$$

Therefore, based on the total number of bundles N_2, that are transmitted successfully in the third and later transmission efforts, (derived in Eq.(12)), RTT, the RTT value for bundle transmissions avoiding CA delay (as calculated in Case I), and, derived in Eq.(7), RTT_{n2_total}, the total RTT value of the N_2 bundles, can be formulated as

$$RTT_{n2\_\text{total}} = RTT \cdot N_2 = \left(2T_{\text{owlt}} + \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}} + \frac{L_{\text{ca}}}{R_{\text{ca}}}\right) \cdot \frac{L_{\text{file}}}{L_{\text{bundle}}}(1 - 2(1 - p_{\text{bundle}}) \cdot (1 - p_{\text{ca}}) + [(1 - p_{\text{bundle}})(1 - p_{\text{ca}})]^2). \tag{13}$$

Therefore, following Eq.(8), using every RTT value for the bundles of a source file, (derived in Eqs.(11) and (13)), the average RTT for the transmission of a source file in bundles—including any CA transmission delay imposed when the bundle size L_{bundle} is shorter than $L_{\text{bundle-min}}$, can be derived as

$$RTT = \frac{RTT_{n1\_\text{total}} + RTT_{n2\_\text{total}}}{NB_{\text{bundle}}} = \frac{\left(\begin{array}{l} \left(2T_{\text{owlt}} + \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}} + \frac{L_{\text{ca}}}{R_{\text{ca}}} + \frac{1}{2} \cdot \left(\frac{L_{\text{ca}}}{R_{\text{ca}}} - \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}}\right)\left(\frac{L_{\text{file}}}{L_{\text{bundle}}} - 1\right)\right)\frac{L_{\text{file}}}{L_{\text{bundle}}} \\ \cdot [2 - (1 - p_{\text{bundle}})(1 - p_{ca})](1 - p_{\text{bundle}})(1 - p_{\text{ca}}) \\ + \left(2T_{\text{owlt}} + \frac{L_{\text{bundle}} + L_{\text{bundle-head}}}{R_{\text{data}}} + \frac{L_{\text{ca}}}{R_{\text{ca}}}\right) \\ \cdot \frac{L_{\text{file}}}{L_{\text{bundle}}}(1 - 2(1 - p_{\text{bundle}})(1 - p_{\text{ca}}) \\ + [(1 - p_{\text{bundle}})(1 - p_{\text{ca}})]^2) \end{array}\right)}{\frac{L_{\text{file}}}{L_{\text{bundle}}}}. \tag{14}$$

3 Numerical results and model validation

In this section, we present numerical results for BP transmission based on experiments on a testbed. Because of paper length limitation, only a few sets of representative results are presented. A PC-based space communication and networking testbed[9] was built to implement an emulated deep-space communication infrastructure. The BP implementation is provided by the Interplanetary Overlay Network v3.2.0[10] developed by the NASA's Jet Propulsion Laboratory.

We used the following configurations in our experiments;

Data channel rate: R_{data}=2 Mbit/s=250 000 B/s;

ACK channel rate: R_{ca}=625 B/s (i.e., with a channel ratio of 400/1);

BP CA segment length: L_{ca}=99 B;

Bundle header length: $L_{bundle\text{-}head}$=28 B;

Here, $L_{bundle\text{-}min}$ can be calculated as;

$$L_{bundle\text{-}min} = \frac{99 \times 250\,000}{625} - 28 \approx 39.6 \text{ KB} \quad .$$

In order to validate the models built for $L_{bundle\text{-}min}$, the minimum size of the bundles, and the RTT value derived in Section 2, we conducted file transfer experiments, Fig.2 compares the average RTT values from the theoretical model with the actual ones measured for the transmissions of a 25-MB file with bundle sizes of 4~64 KB. The RTT values measured from the experiment match the prediction of the model very well, whether the bundle sizes were greater than $L_{bundle\text{-}min}$ or not. This observation indicates that the model built for RTT is valid and it accurately quantizes the effect of CA delay for transmissions with or without delay in CA transmission caused by channel-rate asymmetry.

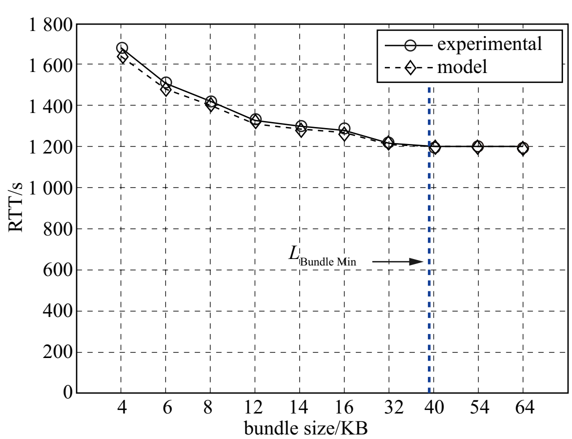

Figure 2 Average RTT values from the experiment and model for transmission of a 25 MB file at a BER of 10^{-6} with bundle sizes of 4~64 KB.

From the perspective of RTT variation, the RTT values from both the experiment and model drastically decrease (from nearly 1 650 s to around 1 200 s) with an increase in bundle size from 4 KB to 40 KB. This is because a significantly long delay of CA transmission is experienced by the file transmission experiment with a bundle size of 32 KB or fewer, and shorter bundle sizes lead to longer delay. For further increases in the bundle size from 40 Kbytes to 64 KB, the RTT is consistently around 1 200 s. Provided that a one-way link delay of 600 s was configured for both the data and ACK channels, there was no delay in CA transmission for the bundle sizes of 40~64 KB because the delay of CA transmission is avoided bundle sizes equal to or greater than 39.6 KB, according to the discussion.

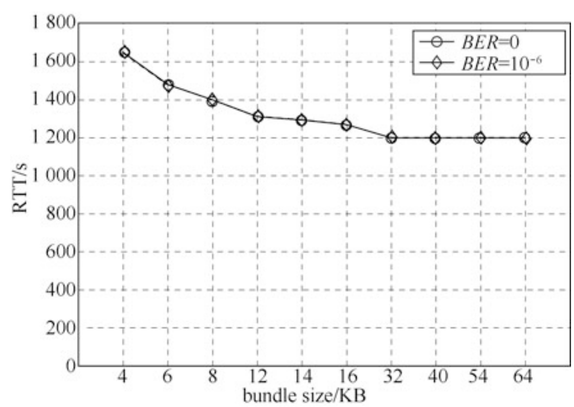

Figure 3 Average RTT values from the model for transmission of a 25 MB file with different bundle sizes and two BERs, 10^{-6} and 0

In the comparison of the average RTT values from the model for different channel BERs in Fig.3, we observe that the average RTT values do not have significant difference for every bundle size from 4 KB to 64 KB at the two BERs. They are almost the same.

4 Conclusion

In this paper, we present the models for the RTT estimation of BP transmissions in deep-space communications. The models were validated by the experimental results using a PC-based testbed. According to both the analytical and experimental results, for transmissions with bundle sizes smaller than a calculated threshold, a smaller bundle size results in a longer delay in CA transmission and thus a longer RTT. For transmissions with a bundle size equal to or larger than the threshold size, the CA delay is avoided and thus, their RTT is consistently very low.

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About the authors

BIAN Zhengguo received his Master's degree of information and telecommunication engineering from Soochow University, Jiangsu, China, in 2015. He currently works as a software engineer in PLAUST (PLA University of Science and Technology), Nanjing, China. His research interests are in satellite communications and deep space communications. (Email: zgbian1989@163.com)

ZHANG Gengxin [corresponding author] received the M.S and Ph.D. degrees from the Institute of Communication Engineer, China, in 1990 and 1993 respectively. He is currently a professor in PLAUST (PLA University of Science and Technology), Nanjing, China. His research interests include the design of communication systems, satellite and deep space communications. (Email: satlab@126.com.)

BIAN Dongming received his Ph.D. degree from PLAUST (PLA University of Science and Technology), Nanjing, China, in 2004. He is currently a professor in PLAUST. His research interests mainly fall in the area of wireless communications, satellite communications and deep space communications. (Email: bian_dm@163.com)