Acknowledgment Mechanisms for Reliable File Transfer over Highly Asymmetric Deep-Space Channels

Lei Yang, Ruhai Wang, Jie Liang, Yu Zhou, Kanglian Zhao, and Xingya Liu

Abstract—**Deep-space network channels are characterized "in part" by asymmetric channel rates. The effect of the asymmetric channel rates is that the slow acknowledgement (ACK) channel cannot effectively support transmission of the ACK segments generated at the data receiver. Increment of data block size and extension of the retransmission timeout (RTO) timer are widely-used transmission mechanisms for eliminating the effect of highly channel-rate asymmetry. The aggregate custody signal (ACS) is recently proposed to resolve the effect of asymmetric channel rates in deep-space networks. In this article, these three acknowledgment mechanisms are studied, with a focus on a comparison of their effectiveness evaluation over highly asymmetric deep-space network channels accompanied by data loss. The study is conducted through realistic file delivery via an experimental testbed infrastructure. It is found that the ACS mechanism shows significant performance advantages over other two mechanisms for both the "normalized" goodput and total data amount in successful file delivery. In particular, the ACS mechanism makes it a better choice to operate with small data bundles without increasing the RTO timer length.**

Index Terms—**Satellite communications, satellite channels, space networks, networking protocols, and deep-space communications**

I. INTRODUCTION

It is well recognized that interplanetary deep-space communications are characterized by the long propagation delays, link interruptions, highly asymmetric channel rates, and high data loss rates. Many studies have been done in developing space architectures and data transmission protocols for reliable data/file delivery in interplanetary deep-space communications and similar scenarios [1-9], including some comprehensive surveys [7-9]. Extensive studies are done in resolving the effect of long link propagation delays, link interruptions and high loss rates. Several transmission mechanisms are also available for eliminating the effect of highly channel-rate asymmetry. Among them, increasing the data block size and extending the retransmission timeout (RTO) timer are commonly recognized as transmission control mechanisms for performance enhancement over highly-asymmetric deep-space channels.

Delay-tolerant networking (DTN) [6] is widely recognized as a key technology in interplanetary deep-space networks [10]. Bundle protocol (BP) [11, 12] was implemented as DTN's core protocol. Fig. 1 shows the DTN protocol stacks that are applicable to space networks [13, 14 (adopted with necessary changes made)]. It is observed that as the core protocol of DTN, BP builds an internetworking overlay to connect heterogeneous networks that can be TCP-based, Licklider transmission protocol (LTP) [15, 16]-based, or UDP-based. Refer to [11, 12] for the details of the DTN and BP protocols. The data units of BP are termed bundles. As the required service of the delay-/disruption-tolerant protocol, the bundles cannot be lost for any reason. In case of link outage/interruption occurred, the bundles are saved in permanent memory. As soon as the link resource becomes available, the bundles are transmitted.

As mentioned, deep-space network channels are characterized "in part" by asymmetric data rates. With respect to the operation of BP, the main effect of asymmetric data rates is that the slow acknowledgement (ACK) channel cannot effectively support transmission of the acknowledging units, termed as custody signals (CSs), generated at the data receiver, which leads to delayed transmission of the CSs. The significantly delayed transmission of the CSs causes either unnecessary premature retransmission of its data units (termed as bundles) at the sender or delayed transmission of the bundles over the opposite channel. As a result of this effect, the transmission performance of the data delivery over space channels, mainly the goodput, is significantly degraded, especially over lossy channels.

For the mentioned two commonly-used acknowledgment mechanisms in resisting highly asymmetric space channels, when applied to BP, they refer to an increment of bundle size and extension of the RTO timer length or interval for bundle retransmission. While both mechanisms are expected to eliminate the delay effect to BP to some extent, they may have negative effects to the transmission performance from other perspectives. The performance of these two mechanisms are discussed in details in Section III.

The aggregate custody signal (ACS) mechanism is recently proposed for BP by the DTN development team in resolving the aforementioned effect of channel-rate asymmetry [17]. There is currently a lack of a solid performance evaluation of the mechanism, especially in a comparative manner (compared with other two mechanisms) when applied in deep-space networks. In this article, the mentioned three acknowledgment mechanisms (i.e., an increment of bundle size, extension of the RTO timer and ACS approach) are discussed, with a focus on a

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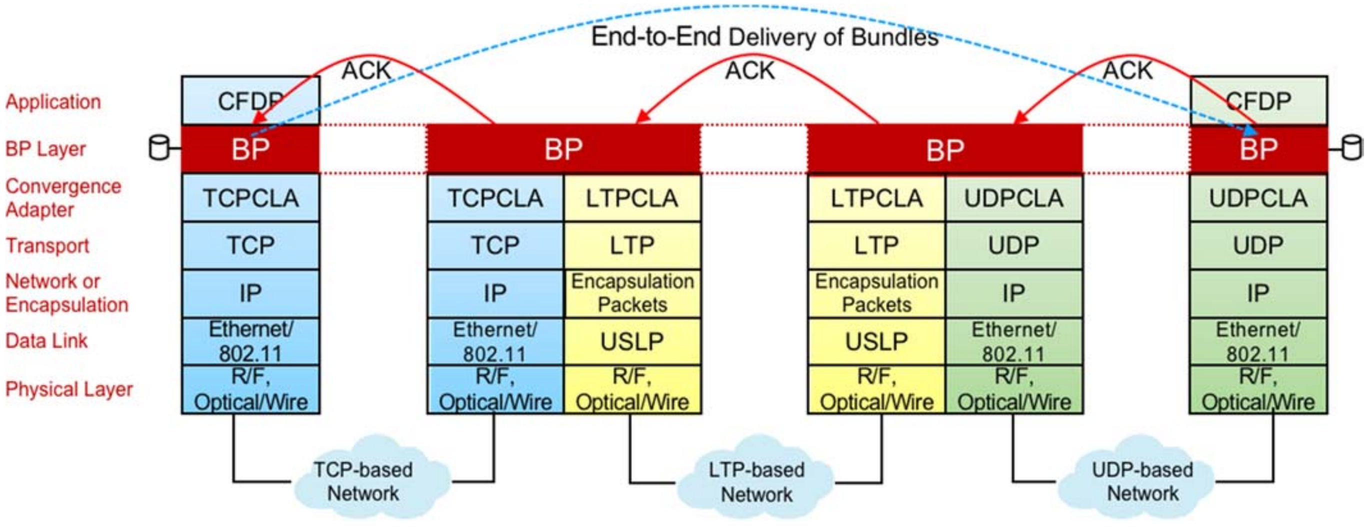

Fig. 1. DTN/BP protocol stacks.

comparison of their effectiveness evaluation over highly asymmetric deep-space network channels accompanied by data loss. The study is conducted through realistic file delivery via an experimental testbed infrastructure.

II. ASYMMETRICAL CHANNELS RATES, ACKNOWLEDGMENT MECHANISMS AND THE PROPOSED ACS

In this section, the effect of channel-rate asymmetry is discussed. A brief overview of the existing acknowledgment mechanisms (i.e., increment of bundle size and extension of the RTO timer length) is presented, followed by an introduction to the proposed ACS mechanism.

A. *Effect of Channel-Rate Asymmetry and Increment of Bundle Size*

To illustrate the impact of asymmetrical channel rates on BP, a transmission scenario of three bundles with highly asymmetric channels is illustrated in Fig. 2. Three bundles are named Bundle$_1$, Bundle$_2$, and Bundle$_3$. The CS$_1$ corresponding to Bundle$_1$ is sent as a reception for Bundle$_1$. However, due to the low data rate of the ACK channel, it takes the receiver longer time to send CS$_1$ than the sender to send a bundle. As a result, before CS$_1$ is completely transmitted, Bundle$_2$ already arrives at the receiver, generating its corresponding acknowledgment information, named CS$_2$. In this case, the receiver cannot send CS$_2$ until CS$_1$ is fully sent. As illustrated, CS$_2$ has to wait for a duration of T_{CS2_wait}. Similarly, for transmission of Bundle$_3$, CS$_3$ has to wait for a duration of T_{CS3_wait} which is the time in waiting for transmission of CS$_2$. Because of the accumulative effect, CS$_3$ has to wait longer than CS$_2$ for transmission of its own previous CS, i.e., $T_{CS3\_wait} > T_{CS2\_wait}$.

If a file having a large number of bundles to be sent, almost all the CS segments have to wait for transmission. While the waiting time for some CS segments is short, the delay accumulated for transmission of the CS segments corresponding to the bundles at the end of the file will be extremely long. Therefore, the round-trip time (RTT) will increase, and in many cases, it will be much longer than the RTO timer length of the bundle because the RTO timer is generally set without the variable waiting time taken into consideration. In this case, some bundles will be retransmitted unnecessarily (or simply, prematurely) upon expiration of RTO timer because they are actually successfully delivered, which leads to excessive and unnecessary amount of data sent at the sender.

For the commonly-used mechanism of increment of bundle size, it refers to configuring the data bundle size larger. Given a file for transfer, the larger the bundle size is configured, the fewer number of bundles need to be transmitted at the sender. Taking the file transfer scenario in Fig. 2 for discussion, if the size of each of Bundle$_1$, Bundle$_2$, and Bundle$_3$ is configured much larger, the entire file will be conveyed by fewer number of bundles for transmission. Provided a “one ACK for each data block” acknowledgment policy, the fewer number of bundles sent at the sender result in fewer CS segments to be sent at the receiver. In other words, the number of CS segments that need to be conveyed over the ACK channel is reduced, and it can even be significantly reduced if the size of the file for transfer is large. This relieves the accumulated long waiting time for transmission of the CS segments over the slow ACK channel because of the highly asymmetric deep-space channels.

B. *Extension of the RTO Timer*

Extension of the RTO timer for retransmission is another widely-adopted method in resolving the effect of channel-rate asymmetry. For most of reliable data transport protocols, the length of the RTO timer in controlling retransmission of data segments is generally configured for the data sender based on an estimated RTT interval, and the RTT interval is estimated from historical RTT measurements. When the configured RTO timer for a data segment expires but its ACK is not received from the receiver, the data segment is considered lost. In this case, the data sender retransmits it. If the RTO timer length is

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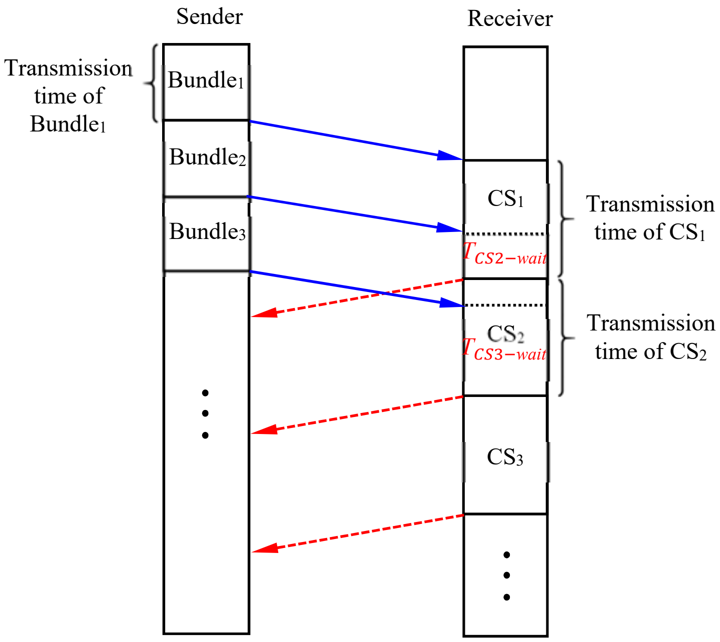

Fig. 2 Data bundle transmission having ACK delay effect involved due to highly asymmetric channel rates.

configured to be too short, the timer expires too often. As a result, some bundles will be retransmitted unnecessarily (or simply, prematurely) upon expiration of RTO timer because they are actually successfully delivered, which leads to excessive and unnecessary amount of data sent at the sender.

The situation is getting worse for the transmission over highly asymmetric channels which introduces the gradually increasing waiting time to the RTT because of the low ACK channel rate. This also makes the RTT gradually increasing. If the file to be transmitted is very large, the RTT can grow substantially long due to the accumulated waiting time, as implied in Fig. 2. In this case, if the RTO timer is configured based on the RTT interval estimated without the additional delay caused by asymmetric channel rate taken into consideration, the timer expires much more frequently and prematurely than necessary. Because the corresponding data segment is retransmitted upon expiration of the RTO timer, it leads to an extensively large number of unnecessarily retransmitted segments at the sender. Following the “one CS for each bundle” acknowledgment policy for BP, it generates unnecessarily a large number of CS segments at the receiver for transmission over the reduced ACK channel. This makes the acknowledging effectiveness worse and eventually leads to catastrophic performance degradation for data delivery over deep-space channels.

To avoid the aforementioned catastrophic transmission situation with the default RTO timer, the RTO timer can be appropriately extended when applied in reliable file transfer in deep-space communications in presence of channel-rate asymmetry. With an extension of the RTO timer length, the timer expires less frequently, which results in fewer retransmissions of the data bundles and therefore, fewer CS segments for transmission at the receiver. The reduced number of CS segments can be effectively conveyed by the reduced ACK channel. This also significantly reduces or totally avoids the long time that the CS segments wait to be sent at the receiver.

C. *ACS Mechanism*

To effectively eliminate the impact of asymmetric channels, the ACS mechanism was proposed in [17] to aggregate multiple CSs for BP’s bundle transmission. In comparison, the ACS and the regular CS sent in response to the receipt of a data bundle (adopted for the earlier discussed approach of the RTO timer extension) are similar with respect to the transmission roles—they both signals acceptance or rejection of custody. Their main difference is that the ACS mechanism extends the CS mechanism so that one or more bundles can be identified and acknowledged in a compressed format. In other words, the ACS mechanism is actually the CS alternative mechanism intended to reduce the number of CS segments so that the constraint of the low ACK channel can be relieved [12].

To illustrate the operation of the ACS mechanism, Fig. 3 illustrates the BP bundle transmission scenarios with and without the ACS mechanism implemented. For the transmission without the ACS mechanism implemented illustrated in Fig. 3(a), there is a one-to-one relationship between the bundle and CS segments. As observed, for each successfully delivered bundle, the data receiver sends a single CS segment. In this case, for file transmission conveyed by a large number of bundles (especially with small bundles), many CS segments are generated at the receiver, which generates a huge data for transmission with the low ACK channel rate.

In contrast, for the transmission with the ACS mechanism implemented in Fig. 3(b), multiple CSs (with each of them corresponding to a single bundle) are aggregated into a single ACS and returned to the sender. In comparison, while a CS segment responds to a single “custodial” bundle, an ACS responds to multiple “custodial” bundles, which avoids transmitting a large amount of the repeated information contained in CSs. This leads to transmission of much reduced amount of data for the CSs over slow ACK channel and thus, a higher transmission efficiency.

The key to the operation of the ACS mechanism is the buffer and window time. The buffer is the area where the custody signals are delayed to be sent, and the window time is the longest waiting time for the CS segments to be sent. Once the window time is exceeded, the custody signals will be sent directly to avoid excessive RTT. As illustrated, denote ACS’s window time as $T_{ACS-Delay}$ After the CSs for multiple bundles are aggregated, the size of the ACS segment must become larger. To ensure that the ACS segments are not blocked at the data receiver, the length of $T_{ACS-Delay}$ should be set the same as the ACS’s transmission time.

As mentioned, the custody transfer is only an optional (non-mandatory) transmission service for BP. This implies that the BP agents (BAs) or the intermediate nodes experienced by a bundle during transfer in the network are either ACS aware or not ACS aware. For a bundle supported by ACS service, a Custody Transfer Enhancement Block (CTEB) is a required block (filled as contiguous sequence of the custody IDs (CIDs)) of the bundle. The CTEB is created to identify the bundle for the ACS service. For a BA which accepts a bundle having the

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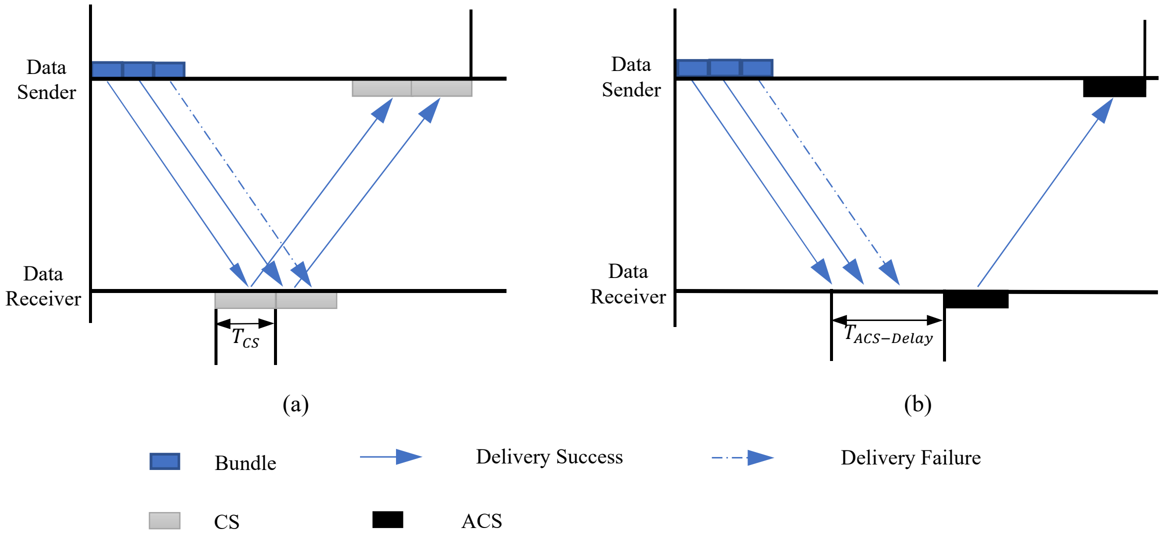

Fig. 3 BP bundle transmission scenarios. (a) With “one-to-one” acknowledgment policy, and (b) With ACS mechanism.

CTEB, the bundles can be processed very differently. The flow chart in Fig. 4 presents the ACS processing of the bundles [12]. The chart explains in details how a data bundle requesting custody transfer service is processed together with the ACS mechanism in different networking scenarios depending on whether or not the BA and the intermediate nodes are ACS capable and they accepts custody.

For transmission with a given channel quality, the loss probability of each independent acknowledgement information carried by each CS in the ACS is determined by the size of the ACS segment. In the case of a highly asymmetric channel ratio or a small bundle size which results in many CS segments, a large number of CSs need to be aggregated with a single ACS, which results in an excessively large ACS segment. Therefore, there is also a limit to the ACS size which is defined as $L_{ACK-Size}$. When a bundle is received, the receiver extracts the CID from the CTEB to identify bundle. The receiver then creates a cached space to save the CID of all bundles received during $T_{ACS-Delay}$. In the window time, the ACS is cached at the receiver, and the CIDs are aggregated continuously until the timer expires. Or, if the size of the ACS is larger than $L_{ACK-Size}$, the ACS at the data receiver is sent immediately. For a detailed discussion of the ACS mechanism, refer to [12].

III. PERFORMANCE COMPARISON AND DISCUSSIONS

The comparative performance evaluation results of the mentioned three acknowledgment mechanisms are presented and discussed in this section. The numerical performance results are collected from realistic file transfer using an experimental infrastructure, space communication and networking testbed (SCNT), which is the same testbed used for the experiments in [18]. We are mainly concerned with transmission performance of total data amount sent and normalized goodput. The SCNT is a PC-based experimental platform which was designed to emulate a typical relay-based space communication infrastructure. It has a capability of emulating various space link delays, random link disruptions, various channel rates and data loss rates. The testbed has been validated [19-25]. The testbed is extensively described in the previous work [18] and thus is not discussed in details here. The Interplanetary Overlay Network (ION) distribution v3.6.2 [17] was adopted as the BP protocol implementation needed for the experiment with and without the ACS implemented with the variations of bundle size and RTO timer length implemented.

Fig. 5 presents a comparison of the data amount and normalized goodput of BP among three acknowledgment mechanisms. The goodput is normalized regarding the amount of data. This implies that the normalized goodput is sort of inversely proportional to the total data amount sent by the sender. The numerical experiment data are obtained from transmission of a 10-Mbyte file with four different bundle sizes. The channel ratio was configured to be 250/1 to emulate the effect of highly asymmetric channel rates. The channel one-way propagation delay and BER are configured to be 10 minutes and 10^{-6}. Two bundle sizes named as Small Bundle (5 Kbytes) and Large Bundle (30 Kbytes) are experimented to evaluate the effect of the variations of the bundle size on the performance of BP. By this, the transmission approach using the increment of bundle size in relieving the effect of channel-rate asymmetry can be evaluated. For the ACS and both bundle sizes, the RTO timer intervals spanning from 1240 sec to 1400 sec are adopted for the experiments, and they are marked as the numerical values on the x-axis. With such a wide range of the RTO timer intervals experimented for each approach, the effectiveness of the extension of the RTO timer are evaluated. For the ACS mechanism, the bundle size is configured to be 5 Kbytes.

A. *Comparison between ACS Mechanism and Other Two Approaches*

For the comparison of the total data amount in Fig. 5(a), it is observed that the transmission with ACS mechanism shows significantly less amount of data than both the small and large bundles for all the RTO timers except the largest timer, 1400 sec. This is an indication that the ACS mechanism has significant performance advantage over the other two approaches except for a very large RTO timer. The ACS

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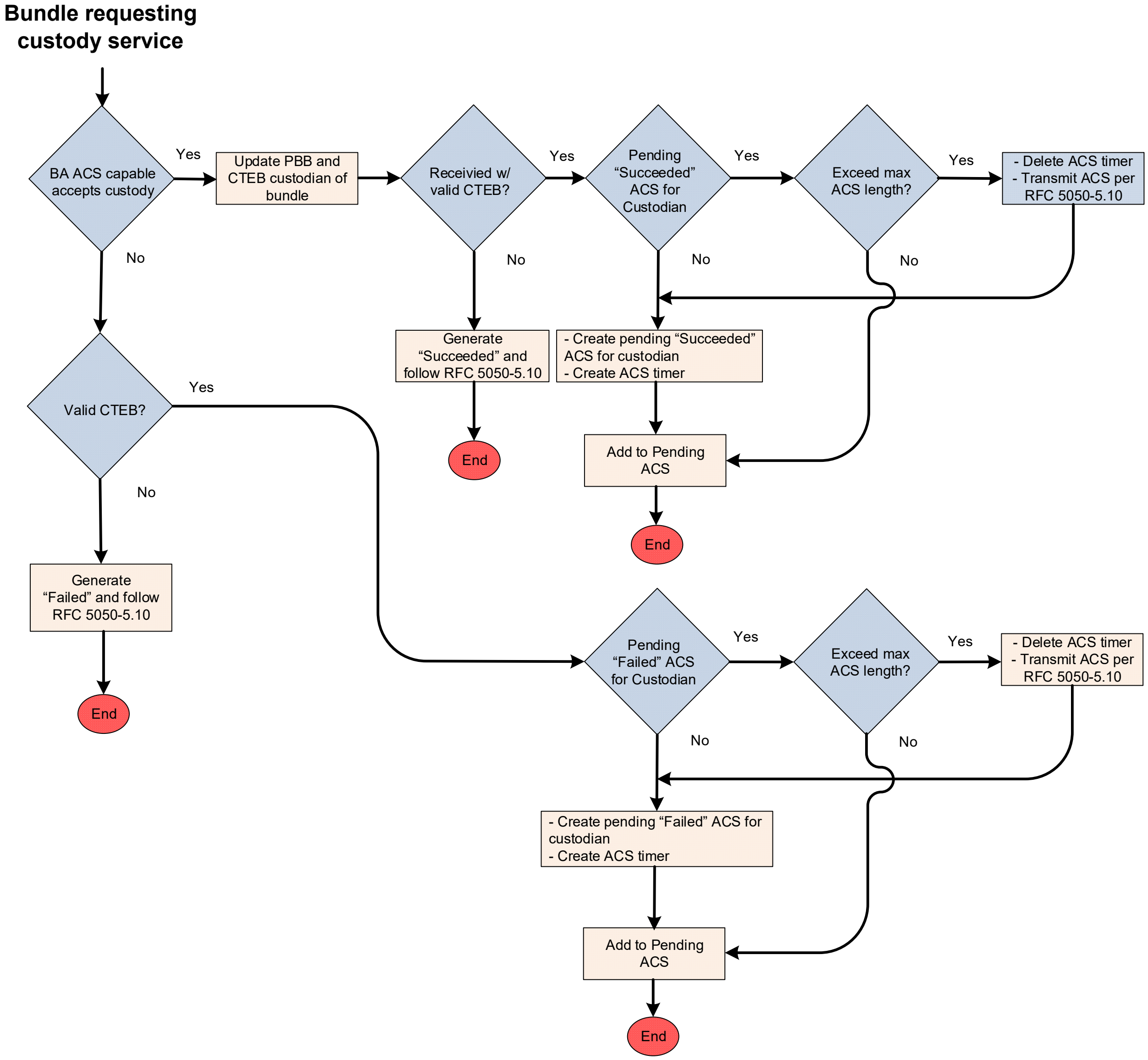

Fig. 4 A flow chart presenting an ACS processing of the data bundles [12, with some changes made].

mechanism and the approach of a small bundle show equal performance with the large RTO timer of 1400 sec. This is because there is no premature retransmission of the bundles made at sender with such a large RTO timer length although acknowledgement delay still occurred at receiver. In other words, the ACS mechanism has no effect on the total data amount with a very large RTO timer because of no unnecessary retransmission attempts made. In comparison, the ACS consistently outperforms Large Bundle (30 Kbytes), which indicates that the ACS mechanisms consistently has significant performance advantage than the increment of bundle size regardless of the RTO timer length adopted.

Regardless of the RTO timer length, the total data amount for the transmission with ACS is consistently around 10.8 Mbytes which is only about 8% more than the application file itself. The channel BER of 10^{-6} caused minor data losses and retransmission of the bundles. It is reasonable that the extra 8% of the total data amount are mainly the transmission overhead and those retransmissions of bundles caused by the channel BER. This implies that for BP transmission, if a small bundle is configured, all unnecessary retransmission of bundles are avoided by the use of ACS even without increment of the RTO timer length.

In comparison, the transmissions configured with other two approaches show enormous data amount, especially for a small RTO timer. Taking the transmission with Small Bundle (5 Kbytes) and a small RTO timer 1240 sec as an example, the total data amount sent at the sender is 17.2 Mbytes which is around 60% more than the one with the ACS mechanism. The huge amount of data was sent because of the small RTO timer which expires early and therefore, results in excessive retransmission of bundles. The bundles were resent because a

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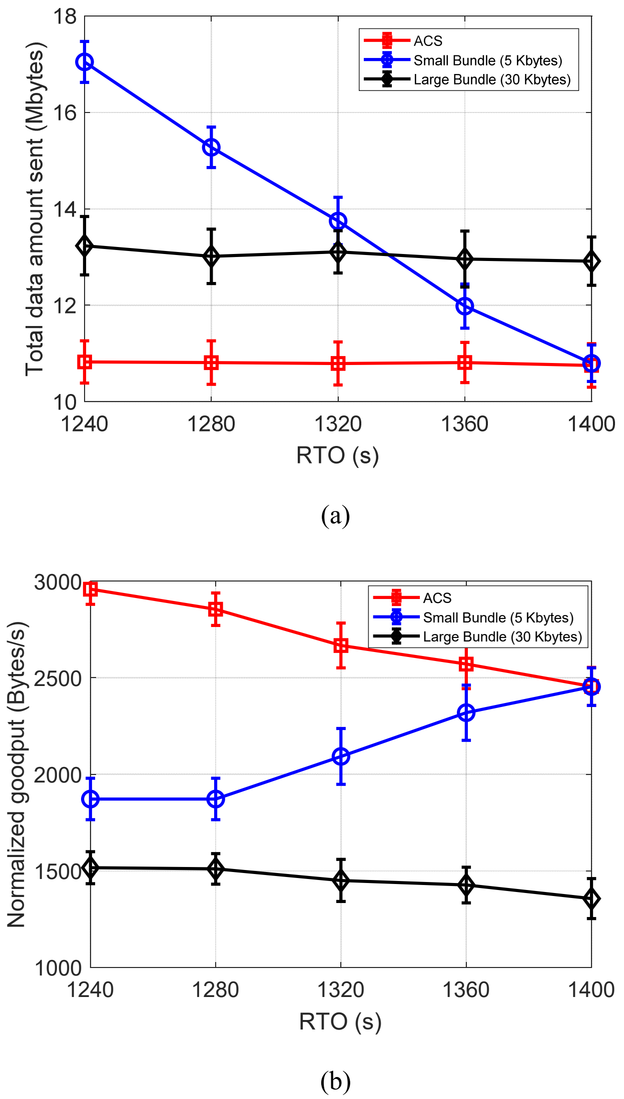


(a)

(b)

Fig. 5 Comparisons of transmission performance for successful file delivery among the acknowledgment mechanisms with extension of the RTO timer length. (a) Total data amount, and (b) Normalized goodput.

large number of CSs were not received when their RTO timer expire. This happens because of the lengthy acknowledgment delay accumulated at the receiver. However, the total data amount decreases with an increase of the timer because when the RTO timer increase which makes the sender wait long for the CS's arrival, fewer retransmission of the bundles occurred and thus less amount of data sent. This implies that the performance advantage of the ACS mechanism over one with a small bundle size are different depending on the RTO timer interval. The most significant advantage occurs with a small RTO timer, and the advantage decreases with increasing timer. This is exactly the observation shown in Fig. 5 (a).

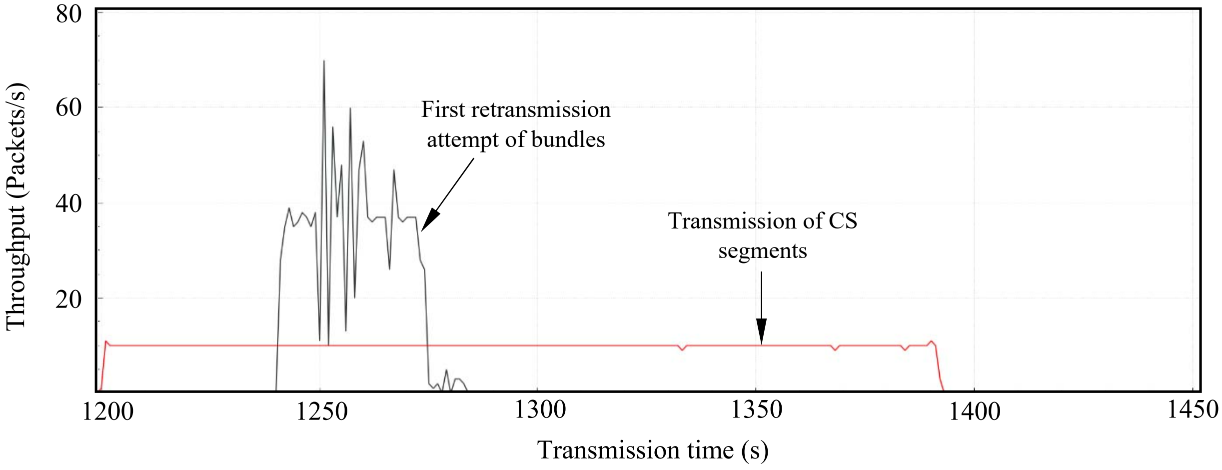
Fig. 5(b) shows a comparison of the corresponding normalized goodput among three approaches. In response to the comparison of the total amount of data sent in Fig. 5(a), the transmission with ACS mechanism shows significantly higher goodput than other approaches for all the RTO timers except the largest timer of 1400 sec at which it performs equally well with the Small Bundle. As mentioned, the normalized goodput is sort of inversely proportional to the total data amount sent by the sender. Corresponding to the data amount variation, the transmission with Small Bundle shows goodput increase with increasing timer. In contrast, for the transmissions with Large Bundle and with the ACS mechanism implemented, the normalized goodput drops slowly although its total data amount remains almost unchanged regardless of the timer length because the file delivery time of the transmission increases with increasing timer. The file delivery time increase because it takes the sender longer time for each retransmission attempt of the bundles as the sender waits until the timer expires to resend the lost bundles.

Provided that the total data amount is unchanged, the decrease of goodput leads to decease of the normalized goodput, as illustrated for the transmission with ACS in Fig. 5(b). However, the transmission with ACS shows significant performance advantage over other approaches for all the RTO timers except the largest timer of 1400 sec at which it performs equally well with the Small Bundle. For both small bundle and large bundle sizes, the performance advantage of the ACS mechanism with a small RTO timer is especially significant. With the timer increasing, the difference in the goodput between the ACS mechanism and other two transmission approaches is declining. The ACS mechanism get merged with Small Bundle around 2500 Bytes/s, with the largest RTO timer, 1400 sec. The performance get merged because of their equal amount of total data sent for successful file delivery, as observed in Fig. 5(a).

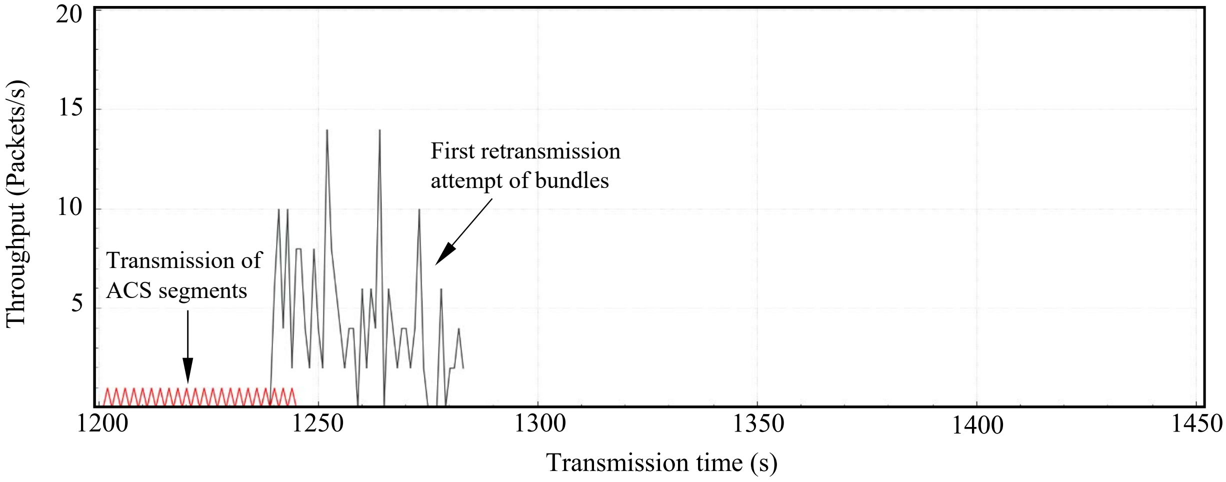
B. Comparison between Small and Large Bundles with Extension (Variations) of the RTO Timer

For a comparison between small bundles and large bundles with extension (variations) of the RTO timer length in Fig. 5, the experimental results show that except the transmissions experimented with a RTO timer interval of 1360 sec or greater, the smaller a bundle size is, more data sent at sender. The transmission configured with Small Bundle (5 Kbytes) generates significantly more data than Large Bundle (30 Kbytes). However, when configured with a very large RTO timer (e.g., 1400 sec), the comparison results are reversed—the transmissions with a large bundle size generates more data than those with a small bundle size. On the other hand, for a given bundle, the larger the RTO timer is, less data is generated. As a result, most data is generated with the smallest RTO timer, 1240 sec, and the least data is generated with the RTO timer, 1400 sec.

The observed variations of the data amount for the changing bundle size and RTO timer lengths in Fig. 5(a) can be easily clarified. Given a file for transfer, the smaller the bundle is configured, a larger number of bundles need to be transmitted at the sender; and as a result, more CS segments need to be sent, and the longer the waiting time is accumulated for the CS segments at the receiver. As a result, more premature retransmissions of bundles are made and thus, the larger total data amount is sent at the sender. That is why the amount of data sent is reduced by increasing the bundle size with a given



(a)



(b)

Fig. 6 Comparison of the throughput traces generated at the sender. (a) With Small Bundle (5 Kbytes), and (b) With ACS mechanism.

RTO timer (except the large timer).

On the other hand, as discussed, the amount of data is reduced by increasing the RTO timer. The reduction is especially significant for small bundles such as 5 Kbytes. This is because increasing the RTO timer interval can reduce the number of bundle retransmissions especially for a small bundle. It is observed that with the Small Bundle (50 Kbytes) configured, the amount of data transmitted decreases significantly with the increase of RTO timer in Fig. 5(a), following an almost linear pattern. However, for a transmission with Large Bundle (30 Kbytes), minor decrease is observed for the data amount in response to the timer increase. This happens because a large bundle does not benefit from increasing the RTO timer because no effect of acknowledgement delay occurs.

For the comparison of normalized goodput in Fig. 5(b), it is observed that the performance for the transmissions with Small Bundle (5 Kbyte) is consistently higher than that with Large Bundle (30 Kbytes). With a small bundle size configured for transmission, the delivery time is actually not much longer compared to the one with a large bundle because its bundle loss probability is lower than a large bundle. The low loss rate results in fewer retransmission attempts of bundles and the shorter file delivery time. Therefore, for a transmission with a small bundle, increasing the RTO timer interval reduces the amount of data sent and achieves a higher normalized goodput, as observed in Fig. 5.

In contrast, regardless of the RTO timer, increasing bundle size makes the normalized goodput drastically dropped. For example, the goodput for transmission with bundle of 30 Kbytes is lowest. In comparison, with the bundle of 20 Kbytes, the goodput performance is increased but it is still lower than Small Bundle (5 Kbytes). This is because the size increase of the bundle in a higher bundle data loss rate results in an increase of the number of bundle retransmission attempts, leading to the drop of the goodput performance. In addition, for transmissions with Large Bundle, a slight decrease of the normalized goodput

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is observed with increasing RTO timer. This is because no effect of acknowledgement delay occurs with a large bundle. Increasing the RTO timer only increases the file delivery time which results in a low goodput and thus drop of the normalized goodput.

In summary, it is obvious that two widely-adopted existing transmission mechanisms (i.e., increasing the bundle size or the RTO timer length) can alleviate the delay for the transmission of the CS segments. However, both mechanisms have negative effects to BP file transfer over asymmetric channels. Increasing the bundle size results in a high bundle loss rate and therefore, increase of the delivery time. This leads to drop of the goodput especially for transmission over a lossy channel. Enlarging the RTO timer causes late retransmissions of the lost bundles and therefore, the delivery time is increased, which leads to drop of the goodput as well.

To illustrate the operational difference during file transfer, Fig. 6 presents the throughput traces generated using the networking analysis toolkit Wireshark [26] for one set of BP transmissions with the ACS mechanism and Small Bundle (5 Kbytes) implemented. The transmissions are done with an RTO timer of 1240 sec. Both traces focus on the file transmission during time interval of 1200-1450 sec for which the first retransmission attempt occurs.

Given a file size of 10 Mbytes configured in the experiments, the file transmission time at the sender is around 40 sec (i.e., $(\frac{(10\times10^6\times8)\ \text{bits}}{2\ \text{Mbits/s}})$. However, for the trace with Small Bundle (5 Kbytes) in Fig. 6(a), it takes around 190 sec (=1390-1200 sec) for all the CS segments to arrive at the sender, which is an indication that serious delay is experienced for the transmission of the CS segments. Obviously, a large number of bundles are retransmitted prematurely (i.e., before their CS are received). This can be observed from the trace that the bundle retransmissions start around 1240 sec and last until 1280 while the CS consistently arrive at the sender during the time interval of 1200 sec to 1390 sec. The CS delay and premature retransmission of the bundles are mainly caused by the small bundle size configured for the transmission which generates many bundles. Given that each bundle generates one CS segment at the receiver, a large number of CS segments are transmitted with the very low channel rate, leading to excessively long CS delay.

In comparison, for the transmission with the ACS mechanism implemented in Fig. 6(b), the enormous acknowledgement delay disappeared. Instead, all the ACSs are completely received at the sender during a period of around 40 sec which has the same length as the file transmission time. This indicates that the transmission of the ACSs experiences no delay. Because of the short time spanned for the ACS reception, the retransmission of bundles starts at the sender around the end of the ACS. This leads to drastic reduction of the total data amount sent for successful file delivery. This clarifies the significantly low data amount measured for the transmission with ACS applied at the RTO timer of 1240 in Fig. 5(a).

In addition, it is observed the amount of data bytes sent in the first retransmission attempt in Fig. 6(a) is significantly more than those in Fig. 6(b). (The data amount sent in the first retransmission attempt is reflected by the area under the retransmission trace.) This is because the one with the ACS mechanism implemented in Fig. 6(b) only retransmits the bundles that indeed lost and requested for retransmission. In comparison, for the one in Fig. 6(a), most of the bundles having the timer configured shorter than the RTT are prematurely retransmitted.

According to the presented performance evaluation, the ACS mechanism resolves the problem of acknowledgement delay and makes the setting of a smaller bundle size a better choice without increasing the RTO timer length. Meanwhile, there is no need to estimate the RTO timer as long as it is set to be slightly larger than $2T_{OWLT}$. Therefore, it is concluded that the ACS mechanism has significant performance advantages compared to two widely used existing methods (i.e., increasing RTO timer and bundle size).

IV. SUMMARY AND CONCLUSIONS

The ACS mechanism is proposed for DTN' core protocol, BP, in eliminating the delay effect caused by asymmetric channel rates. The ACS mechanism operates by aggregating multiple CSs (with each of them corresponding to a single bundle) into a single custody signal segment which conveys the information about the transmission status of multiple "custodial" bundles and avoids transmitting a large amount of the repeated information contained in CSs.

A study of the ACS is presented based on experimental data, focusing on its effectiveness evaluation over highly asymmetric deep-space network channels accompanied by data loss. This study is conducted in a comparative manner by comparing the ACS mechanism and the widely-used existing mechanisms including increasing bundle size and extending RTO timer interval mechanisms. Both the existing transmission mechanisms are able to eliminate the acknowledgment delay effect but lead to a low transmission efficiency. The comparisons show that in additional to effectively eliminate the effect of acknowledgement delay, the ACS mechanism shows significant performance advantage in the data amount and normalized goodput for successful file delivery. In particular, the ACS mechanism makes it a better choice for BP to operate with small bundles without increasing the RTO timer length.

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