Bundle Layer End-to-end Retransmission Mechanism

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***Abstract*—Delay Tolerant Networking (DTN) has been proposed as a global overlay architecture to provide network connectivity in challenged environments such as deep-space communications field. Bundle Protocol along with its convergence layer protocols transform end-to-end reliability into questionable hop-by-hop reliable communication and imposes a two-tier routing policy that allows flexible routes only within regions. In this paper we propose a Bundle layer end-to-end reliability mechanism (BLER) and evaluate its performance in a DTN testbed in conjunction with similar mechanisms. We highlight the advantages of BLER mechanism in space communication scenarios which cannot be adequately addressed by the current DTN architecture and hop-by-hop reliability mechanisms in general.**

***Index Terms*—Delay Tolerant Networking, deep space communications, end-to-end reliability, retransmission mechanism.**

I. Introduction

SPACE communications typically rely on scheduled links and require less sophistication from communication protocols. In this context, the link layer was the dominant layer for space communications; routing was never an issue; end-to-end reliability was frequently overlapping with reliability of a single hop; congestion and overflow were absent due to strict scheduling of communication activities and admission control; and the limited required sophistication was shifted to the application layer.

However, two new major properties have changed the spectrum of potential architectural choices for space communications: (i) the multihop architecture, which is required to reach deep space and (ii) the increasing number of alternative communicating paths that may be used to reach a single receiver. Inline with these two properties, the demand for interoperability among space agencies has also contributed towards the emerging field of Delay Tolerant Networking (DTN) [1]. The DTN architecture [2] and the accompanying Bundle Protocol (BP) [3] specification documents present a means for data communication on potentially heterogeneous networks characterized by high delays or disruptions. Nevertheless, the DTN architecture alone cannot cope with these challenging environments. It essentially glues together dissimilar protocol stacks, but it relies upon underlying network services adapted to the special networking conditions.

DTN's storing functionality and its property to delegate custody seem to match two major requirements for space communications: one is the requirement for permanent storage due to long interruptions in space communications; the requirement for hop-by-hop reliable communication until the receiving end. However hop-by-hop reliability cannot guarantee application reliability. This is not a new argument; rather, it has attracted major attention from the internet community and resulted in the well-known "end-to-end argument", which claimed that end-to-end monitoring allows for more complete administrative approaches than the administration of intermediate hops.

The custody feature of DTN involves also some undesirable properties. For example, it may be possible for a bundle to be delivered to some node, which becomes isolated after having accepted its custody but prior to forwarding it to another node. Given a single custodian per bundle, data transmission freezes in such cases, even when there are alternative routes from source to destination. In this context, scenarios discussed later in the paper, evince that Bundle Protocol does not really provide end-to-end service. Furthermore, in order to enhance BP, we propose a new mechanism namely "Bundle Layer End-to-end Retransmission Mechanism" (BLER) in order to provide end-to-end reliability service. In addition we evaluate its performance in a testbed, in conjunction with custody transfer and flooding, Bundle layer reliability mechanisms. In particular, BLER allows for bundle retransmission from the original sender, until reception of delivery report from the final recipient or retransmission timer expiration. We present here results that compare the performance of the aforementioned mechanisms in terms of completion time, using different values for propagation delay, filesize and packet error rate, which affect highly the data delivery. We conclude that in certain scenarios BLER mechanism's end-to-end communication is the only functional solution, compared to the other mechanisms and therefore the overhead it imposes

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is justified.

The remainder of the paper is organized as follows: in Section II we briefly discuss recent DTN routing approaches that use multiple copies in order to achieve reliable transfers for both terrestrial and space communications. In Section III we discuss the most prominent Bundle layer reliability mechanisms and we propose a new one, named BLER mechanism. The aforementioned mechanisms are evaluated through a series of experiments in Section IV, focusing on space communications. Finally, in section V we conclude on the value of an end-to-end reliability mechanism that could enhance BP.

II. Related Work

Although typically reliability has been transport layer's inherent feature, the specificity of DTN protocol stack renders reliability a complicated issue. More specifically DTN operates as an overlay, allowing for two-tier routing policy, placing BP above transport layer. Regarding space communications, successful data delivery in DTN is based on transport layer which operates in a hop-by-hop fashion and Bundle layer routing performed at each node. In that context, lack of end-to-end mechanisms renders routing even more crucial. In this work we focus on routing and Bundle layer mechanisms that guarantee bundle delivery.

Successful data delivery in challenging environments can be exceptionally difficult or impossible. Intermittent connectivity is a typical characteristic of such environments, while even in case of predefined contacts there are imponderable factors such as physical phenomena. Moreover network and node resources are also limited, while topology information may be incomplete or obsolete. A category of routing algorithms attempts to compensate the lack of knowledge by spreading multiple copies of a message to the network, namely flooding algorithms.

Epidemic routing, a flooding-based technique which belongs to this category has been proposed in [4]. Although this method manages to find the best route towards destination (assuming there is one), it consumes greedily energy, bandwidth and storage resources. MaxProp [5], another flooding-based routing algorithm, attempts to mitigate the problem of resources exhaustion by suppressing redundant transmissions and applying queue management, dropping policies and acknowledgements, in order to prioritize packets with better probabilities to reach their destination and remove stale information from buffers.

Some approaches attempt to reduce Epidemic routing overhead by forwarding a message's copy with a probability p [6] or by spreading copies only to those nodes that have higher probability to deliver the message (probabilistic routing [7]). A hybrid flooding-probabilistic routing technique has been proposed in [8], where flooding and probabilistic protocols are switched depending on the number of available contacts.

Other algorithms combine characteristics of both single and multi-copy schemes by spreading a fixed number of replications per message ([9], [10]). The combination of those algorithms with erasure coding techniques in order to maximize the delivery probability has been studied in [11] and [12].

Routing algorithms with no knowledge about the connectivity pattern, traffic demands and available resources usually fail to perform efficiently; in contrast with efficient algorithms using limited additional knowledge. These algorithms are aimed for networks where contacts are scheduled rather than opportunistic, such as interplanetary networks. In [13] the performance of algorithms with increasing knowledge about the network's parameters is investigated.

Although these methods manage to increase the probability of successful transfer, they cannot guarantee reliability. Even in interplanetary networks where contacts are scheduled, other parameters such as traffic demand and resource availability cannot be known in advance. Moreover, high packet error rates are quite common and affect data transfers at a great extend. Thus, a path which is regarded to be optimum, according to a knowledge-based routing algorithm, could eventually induce an unexpected delay and cause bundle's time-to-live (TTL) expiration.

Delay Tolerant Transport Protocol (DTTP), a protocol with both transport and network layer characteristics designed for delay tolerant networks, has been proposed in [14]. DTTP allows dynamic routing, as each node is able to adapt its routing decisions autonomously according to measurements about each path's performance. Moreover, DTTP offers end-to-end reliability by utilizing reliable hop-by-hop transfer and delegating the responsibility of data transfer to the next node on the path to final destination.

In [15], the advantages and disadvantages of an end-to-end transport protocol on top of BP are investigated. The authors suggest that an end-to-end monitoring service would allow for increased reliability and present specific scenarios where DTN architecture cannot cope based on hop-by-hop reliability. Furthermore end-to-end service is claimed to allow optimal source routing, while DTN routing should become a source-oriented service.

Contact Graph Routing (CGR) [16] is a routing protocol based on scheduled contacts, particularly useful for space communications and was selected for the evaluation part. The proposed mechanism complemented Bundle layer functionality with end-to-end reliability functionality, while CGR was responsible for route selection.

III. Bundle Layer Reliable Transfer

Delay tolerant networks are characterized by intermittent connectivity, asymmetric links, high propagation delays and high packet error rates; therefore the use of a pure end-to-end transport protocol is prohibited. However, end-to-end functionality can and should be integrated into Bundle layer. Even though the underlying transport protocols provide reliability, there are mechanisms at Bundle layer which ensure bundle delivery. In this section, we present such mechanisms, namely custody transfer and flooding, along with BLER, a new mechanism which we propose.

A. Custody Transfer

BP incorporates an optional feature called custody transfer, in order to offer reliable hop-by-hop transmission to the final destination. According to custody transfer mechanism, bundles are transmitted in a "Store-and-forward" technique while the responsibility of reliable transfer is delegated to the next node in a route towards the final destination.

A node which receives custody of a bundle is called custodian. The custodian node must forward the bundle to a neighboring node requesting custody transfer. The neighboring node will reply with a custody acceptance or custody refusal signal, according to its admission control policy. The ability to forward the bundle to the final destination before TTL expiration and resource availability, are the basic criteria each receiving node evaluates. In case the custodian node does not receive a reply within a specific time interval, a timer triggers the bundle's retransmission, possible through a new route. The custodian is obligated to store the bundle until the reception of custody acceptance signal upon which the bundle is discarded, or until the expiration of bundle's lifetime. Therefore, there is only one custodian node in a DTN which is responsible for the delivery of the specific bundle and in case this custodian node becomes unavailable to the network, there is a high probability the bundle will never be delivered and the data will be lost.

B. Flooding

Bundle delivery in DTN, using custody transfer mechanism, is strongly depended on the selected route towards the destination. A non-optimum routing decision could induce significant delay to the transfer of important data that should be "immediately" delivered encapsulated into critical bundles, or even worse cause TTL expiration. This fact necessitates the existence of a different approach regarding critical bundles which must in any case reach their destination as soon as physically possible.

Interplanetary Overlay Network (ION) [17], software that implements the DTN architecture as described in Internet RFC 4838, has applied the routing method of flooding for bundles that are marked as critical. Instead of calculating a single route that is considered to be "best" according to CGR, critical bundles are queued for transmission to each neighboring node that is able to successfully transmit them to their final destination. Flooding guarantees that critical data will be delivered with the minimum latency. However, this method induces significant overhead in terms of bandwidth and data storage.

C. BLER mechanism

Lack of end-to-end monitoring of data transmission renders custody transfer mechanism inadequate to guarantee reliability at certain cases. Consider the scenario where the custodian node is not able to forward the bundle before its TTL's expiration due to unexpected events (e.g. connectivity problems or node failure). There is no other copy of the bundle available, thus the bundle will never be delivered. Consequently, the existence of a mechanism which could handle effectively the "missing bundle" problem seems to be indispensable.

We have designed and implemented a mechanism which extends ION's implementation of Bundle Protocol, in order to find a satisfactory solution to the "missing bundle" problem and offer guaranteed transfer for critical data. Our goal is to ensure that critical bundles will reach their final destination within a minimum period of time, provided that the initial sender is operational and there is a route to destination. We have combined point-to-point reliability that custody transfer mechanism provides with end-to-end acknowledgements at the bundle layer in order to allow initial sender to monitor the transfer of critical data and detect failures.

According to our approach the initial sender stores the data along with additional information for each critical bundle such as destination, TTL and creation time. This information will be stored until the reception of an acknowledgment from the final destination or the expiration of bundle's TTL field. The critical bundle is being sent using custody transfer, while in addition end-to-end communication is achieved due to BP status reports, as defined in the specification [18]. Each critical bundle is created with status report on delivery flag activated, thus the final recipient will sent a delivery status report back to the initial sender as an acknowledgement.

Whenever a critical bundle is created, a timer is activated and in case the acknowledgement does not arrive during a specific time period, the timer expires and triggers the creation of the critical bundle's copy. A new route will be computed based on current routing information and the bundle will be transmitted requesting custody acceptance. Moreover, information for the new copy of the critical bundle, such as creation time, will also be stored and a retransmission timer will be set accordingly.

Retransmission timer is crucial for the performance of the mechanism. A low value would cause redundant retransmissions, while a high value would unnecessarily prolong the delivery. For this purpose, information provided by CGR is utilized. CGR includes information about bandwidth and propagation delay between each pair of nodes, as well as the connectivity map of the complete topology. Thus, reliable estimation of the round trip time (RTT) from the initial sender to the final receiver is feasible.

Adjusting the aforementioned timer properly can reduce meaningless retransmissions. However, it is possible that the initial sender may receive multiple acknowledgements for the same bundle due to delays. In the latter case, the reception of the first acknowledgement will cause the deletion of all information associated with the critical bundle and the pending timer will be canceled.

Status report delivery from the final destination to the initial sender may be a time-consuming procedure due to limited connectivity and high propagation delays. However, the proposed mechanism adds end-to-end functionality to BP and copes with node and link failures in contrast with custody transfer, while inducing significantly less overhead in terms of bandwidth and storage compared to flooding mechanism.

IV. Simulation Results

BLER mechanism comprises a reliable, end-to-end approach that guarantees data delivery if a route is available and resolves reliability issues of underlying hop-by-hop transport protocols. The mechanism can be applied to a variety of heterogeneous networks, since it is implemented at Bundle protocol's layer, allowing the use of a variety of accompanying transport protocols. More specifically, we integrated the mechanism into JPL ION [17] DTN reference implementation, designed primarily for space communication, and evaluated it in conjunction with ION custody transfer and flooding using the ESA/ESOC DTN testbed [19] which we host at our lab. Moreover, a series of different scenarios and topologies was exploited which are divided into three main categories, namely: Operational, Performance and Future scenarios, focusing on space internetworking.

Operational scenarios were used in order to measure the performance and the induced overhead of each mechanism in a simple topology. These experiments allow for an initial overview of the differences between the mechanisms. Performance scenarios evaluate the mechanisms in realistic space communication conditions. Future scenarios comprise representative space to Earth communication scenarios, where scheduled connectivity is lost; subsequently current reliability mechanisms do not perform efficiently or at all, while the proposed mechanism guarantees data transfer imposing minimum overhead.

Licklider Transmission Protocol (LTP) [20] is designed to provide retransmission-based reliability in hop-by-hop fashion and is principally aimed at operating over deep-space RF links. Furthermore LTP is compatible with DTN architecture, therefore it was used throughout the experiments; specifically it serves as a reliable "convergence layer" protocol, underlying Bundle protocol.

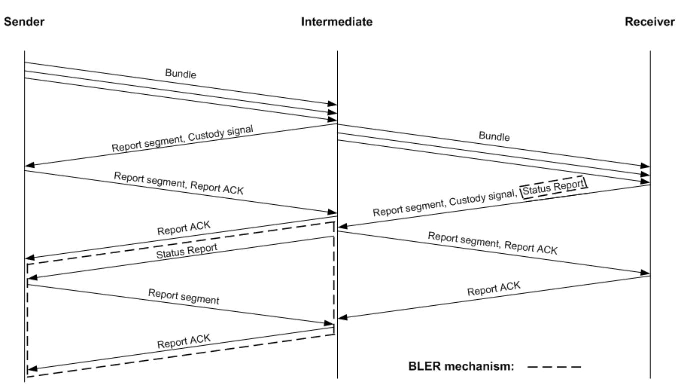

Figure 1 Packet exchange during two hop Bundle transfer

In order to highlight the differences between the mechanisms, Figure 1 depicts the sequence of exchanged LTP Reports, LTP Report ACKs, Bundle Custody signal and Status Reports during a two hop Bundle delivery using custody transfer. The additional communication overhead of BLER mechanism is also presented in Figure1. Flooding exchanges the exact packets as custody transfer per hop, although for every available hop in the network. Note that the transfer of a single bundle from a sending node to the next cannot begin until complete reception of the entire bundle, according to Store and Forward technique.

Regarding the results, total completion time was the performance parameter for the experiments, while the end of the examined mechanism was considered as the end of the experiment. In addition, each value in the figures derives from the average of thirty experiments.

A. Operational Scenarios

In order to compare the mechanisms and highlight their differences in functionality and overhead, initially we used a simple rhombus topology as depicted in Figure 2 with constant connectivity. We evaluated the three reliability mechanisms using various file sizes in order to study the computational overhead, and various propagation delays as to elaborate on the overhead induced by the exchange of reports and acknowledgements.

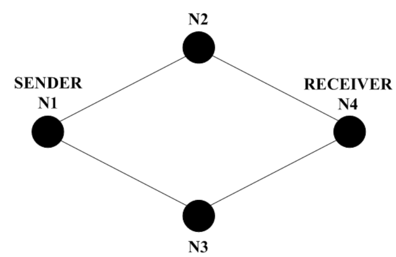

Figure 2 Network topology

1. File size

In order to study the differentiation of computational cost for each mechanism, we used various file sizes namely 1, 10, 100 KB and 1 MB, encapsulated in a single bundle, using LTP segments of 1400 Bytes. Packet Error Rate (PER) and propagation delay were both set to zero for all links, while bandwidth was 1 Mbps.

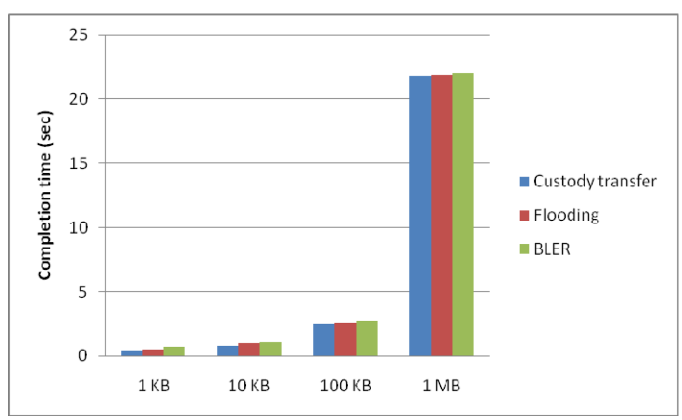

Figure 3 File size 1, 10, 100 KB and 1 MB

Figure 3 depicts transfer completion times for each of the mechanisms using different file sizes. Note that increased completion times are justified by ION software computations due to file size. Custody transfer requires the least data exchange and thus achieves the lowest completion time. Flooding transmits twice the data of custody transfer; therefore the variation in completion time is due to additional computations at the nodes. On the contrary BLER mechanism uses very few additional reports (Figure 1) more than custody transfer, but achieves the highest completion time due to end-to-end communication. Nonetheless, these reports impose insignificant overhead to the bandwidth of the network, since their size is in the order of tens of KB.

2. Propagation delay

The second category of Operational scenarios is focused on the impact of propagation delay on the performance of each mechanism for both terrestrial and space communication. Therefore propagation delay ranges from 0 to 30 seconds, a 1 MB bundle is sent with 0% PER and 1 Mbps bandwidth.

Figure 4 highlights the impact of propagation delay increase on total completion time. Custody transfer and flooding require quite similar time to complete Bundle transfer in each experiment, while on the contrary BLER mechanism is the most time consuming due to additional exchange of reports – packets (Figure 1). The excess time required by the proposed mechanism in these scenarios is approximately equal to the propagation delay of the last Report ACK packet. Therefore it is obvious that in case a topology consists of multiple hops with high propagation delay, the performance of BLER mechanism regarding completion time degrades significantly.

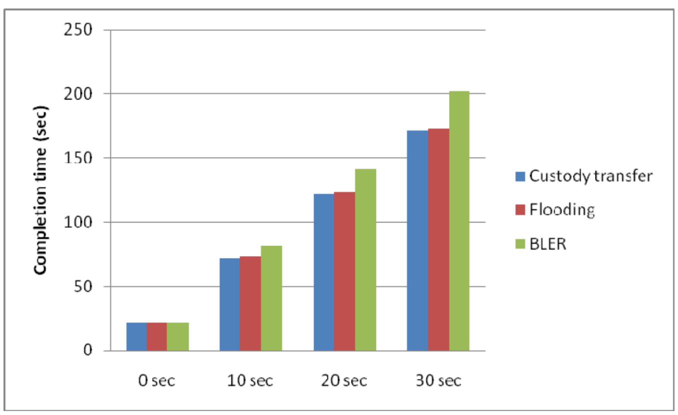

Figure 4 Propagation delay 0, 10, 20, 30 seconds

B. *Performance Scenarios*

The specific scenarios emulate data transfer in space communication conditions exploiting several parameter values in order to study the performance of each mechanism. The basic rhombus topology of Figure 1 is supplemented with various PER, propagation delays, bandwidth and file sizes. Emulation topology represents a Rover on the surface of a planet which sends measurements and photos to the Command Center on Earth through two possible intermediate Satellites located near the planet, as depicted in Figure 5.

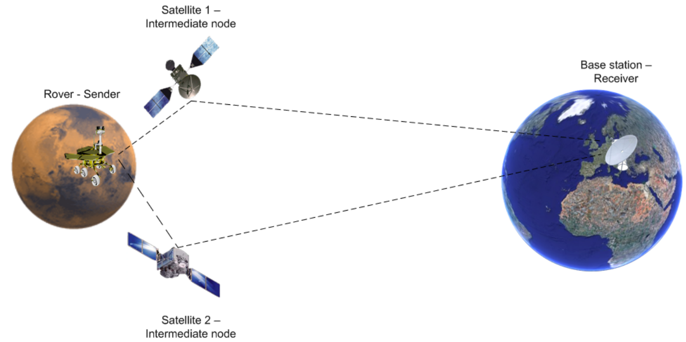

Figure 5 Performance scenarios' network topology

Communication parameters are adjusted in order to correspond to realistic conditions, therefore the links between the satellites and the rover are set to 1.6 ms propagation delay, 200 Kbps bandwidth, while the links towards Earth are set to 30 sec propagation delay and 500 Kbps bandwidth. We used two set of experiments based on the aforementioned parameters, setting PER to 0%, and then 0.1% for the links between the satellites and the rover, while the links towards Earth were set to 0% and 1%. The different sets correspond to the cases where the link layer can repair or not the occurred bit errors. Emulated topology is assumed to have constant connectivity and file sizes are 100KB and 1MB.

Non zero PER imposes a significant overhead (Figure 6) due to retransmissions, although the performance of the mechanisms is quite similar. The aforementioned results have evinced that BLER mechanism underperforms in terms of time completion compared to both custody transfer and flooding. End-to-end functionality proved to be redundant for the specific scenarios since the underlying LTP protocol was able to transfer data reliably on a hop-by-hop basis. Increasing propagation delay, adding more hops to the route or adjusting intermittent connectivity between nodes, would highly degrade proposed mechanism’s performance. However the aforementioned scenarios represent space communication which is rather static due to predetermined contacts, centrally controlled, while failures of any kind are excluded.

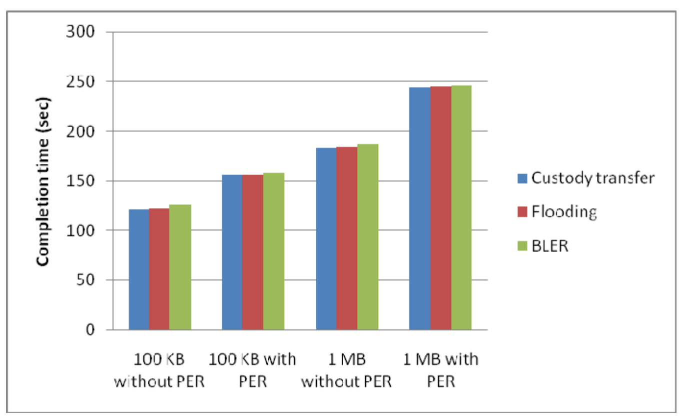

Figure 6 Results with and without PER

C. *Future Scenarios*

Future scenarios refer to space communication scenarios where there are numerous nodes that share resources, connectivity cannot be predicted to a large extend or may be lost as well due to node failure, physical phenomena, storage or battery depletion, thus dynamic routing is required. Moreover terrestrial ad hoc networks are characterized by similar attributes as well. Hop-by-hop reliability can be compromised in such cases, while on the contrary end-to-end reliability mechanisms such as BLER perform efficiently.

1. Node Failure

Node failure or "missing bundle" scenario comprises a custodian node which shuts down unexpectedly. Using rhombus topology (Figure 1) intermediate N2 node shuts down after it receives custody of a bundle. In case the node is not able to resume soon enough, connectivity may be lost, bundle's TTL may expire and there is no other copy in the network according to simple custody transfer mechanism.

Using the topology and settings of Performance scenarios with PER for a 100KB file, BLER mechanism completed the transfer in 313.9 seconds, while retransmission timer was set to double RTT, 190 seconds, in respect to scenario's attributes. Moreover flooding completed the transfer in 156.5 seconds by retransmitting multiple copies of the bundle. Delay versus bandwidth and storage tradeoff is quite perceivable in this scenario.

2. Lost Link

Currently space communications are based on predetermined contacts and on the fact that nodes are fully aware of the network topology and link attributes. In the future we expect the number of communicating space assets to increase, thus it would be unlikely to use a link state proactive routing approach and maintain tables about a large number of nodes. Lost link scenario comprises the case where an initial sender routes a bundle through a specific path, although it is not informed that an intermediate link is lost as depicted in Figure 7.

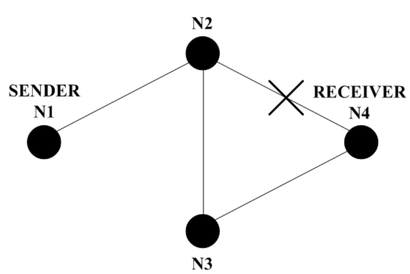

Figure 7 Lost link scenario

Intermediate custodian node N2 will select a new route, based on its routing information through node N3; therefore custody transfer will deliver the bundle to the destination. BLER mechanism would retransmit the bundle based on the knowledge of the initial sender which may be updated or not when retransmission timer expires, thus the actual route the Bundle follows may be either longer or shorter than the one the initial sender computed. BLER mechanism uses custody transfer between nodes; therefore the bundle will also be delivered through node N3, while there might be redundant retransmissions.

For instance in case there is constant connectivity using the topology of Performance scenarios with PER, custody transfer mechanism requires 197 sec, while BLER mechanism delivers data the exact time Custody transfer does and is completed in 387 sec. However in case a new 'shorter' route, in regard to time, appears between nodes N1 and N3 when BLER retransmits the bundle, the initial sender will be able to exploit it and achieve lower completion time than custody transfer. Such a case may be rare in space, but is quite common in terrestrial ad hoc networks where BLER could be applied and achieve better performance than custody transfer.

V. Conclusions

DTN architecture is the most prominent solution for space communication; however in the near future it cannot rely on centralized control and the robustness of the network. Underlying transport layer hop-by-hop reliability does not necessarily guarantee application reliability; simple custody transfer may not allow for timely completion of application task; and hop-by hop routing may not exploit the best available path from source to destination.

We have highlighted occasional benefits from a DTN end-to-end retransmission mechanism; moreover we have designed and implemented a Bundle layer end-to-end retransmission mechanism that enhances DTN custody transfer mechanism utilizing Bundle protocol's inherent reports. We have evaluated the proposed mechanism for space communication scenarios in conjunction with custody transfer and flooding and highlighted its efficiency where the other mechanisms underperform. In addition BLER mechanism can also be applied to terrestrial networks and allow for end-to-end reliability at Bundle layer.

We plan to design a dynamically adjustable timer that will adapt in correspondence to network properties. This feature will allow for increased responsiveness and performance in general. Finally, we intend to further improve the mechanism using redundancy and load balancing, in order to achieve higher reliability while minimizing delay.

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