DTN LEO Satellite Communications through Ground Stations and GEO Relays

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Abstract. LEO satellites are characterized by intermittent connectivity with their ground stations. Contacts are short and separated by long intervals, which with urgent data can become a critical factor. To solve this problem, the use of GEO satellites as relay has recently been suggested. This solution is appealing, but has some limits, especially with polar orbits, as the link between the LEO satellite and the GEO relay is affected by long disruptions over polar regions. Moreover, the bandwidth available may be limited and difficult to fully exploit. In this paper, we show that GEO relays are complementary rather than alternative to ground stations, and that the enabling technology for their combined use is DTN (Delay-/Disruption- Tolerant Networking) architecture and related protocols, including CGR (Contact Graph Routing). To demonstrate this, a series of experiments carried out on a testbed running ION, the NASA implementation of the DTN protocols and CGR, is discussed in the paper.

Keywords: Delay-/Disruption- Tolerant Networking (DTN), Satellite Communications, GEO relays, Earth Observation, Bundle Protocol, CGR.

1 Introduction

LEO (Low Earth Orbit) satellites are characterized by a much shorter distance from Earth than GEOs have (LEOs 160 - 2000 km; GEOs, 36000 km). This short distance is essential in Earth observation and it offers the additional advantages of lower path loss and shorter propagation delay. However, because of the low orbital height, LEO satellites move fast in the sky, as seen by a terrestrial observer, and can be in Line Of Sight (LOS) with a ground station for only a few minutes each contact. While a LEO satellite moves along its orbit, the Earth rotates around its polar axis, which is an advantage for Earth observation, as different regions are covered by the same satellite at each orbital period, but also implies that a LEO satellite does not pass over the same ground station every orbital period.

To quantify the time connectivity of a LEO, let us focus on a typical Earth observation satellite. Assuming an orbital height of 700 km, we have a period of about 100 min and contact lengths of roughly 10 min. Although the minimum time interval between consecutive contacts is one orbital period, it is generally longer,

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depending on the orbit of the satellite and the latitude of the ground station. In order to provide a global coverage, the orbit has to be polar or close to polar. In such a case, for a ground station close to the pole we have a contact each orbit, while moving towards the equator we have groups of a few consecutive contacts (one at each orbit), separated by much longer intervals.

By contrast to GEO satellites, which have usually continuous connectivity, the link between a LEO and a ground station is characterized by short contacts separated by long intervals. The channel is therefore intermittent, but known a priori, because related to the deterministic satellite and Earth motion. This kind of connectivity, which can be suitably classified as scheduled intermittent, cannot be tackled by ordinary TCP/IP protocols, but can be easily handled by DTN (Delay-Disruption-Tolerant Networking) [1], [2], [3], [4]. In fact, apart from the much shorter propagation delay, it is the same kind of intermittent connectivity as in deep space networks, for which DTN was conceived [5]. Using DTN architecture and protocols in LEOs was actually suggested in the original DTN standardization document [1] and some preliminary experiments on a real LEO constellation have been successfully carried out [6]. This has also been investigated by some of the present authors [7], [8], [9], and is also suggested here, where, however, a more complex scenario is involved.

For some applications (e.g. disaster monitoring, military observation) the variable but generally long delay between data creation and data availability at the LEO control centre is a clear disadvantage. A partial remedy is the use of multiple ground stations. A more radical and innovative solution is using a GEO satellite, or a GEO constellation, as a relay, as suggested in [10], [11], [12]. In particular, in [12] Inmarsat promotes the use of its Inmarsat-4 GEO satellite constellation and the BGAN ground network to establish bi-directional near-continuous IP connectivity between a LEO satellite, its control centre and remote users. Although appealing, this solution too is not problem free: LEO-GEO connectivity is not continuous, but more precisely scheduled intermittent, at least for LEOs on polar orbits, because of the GEOs well-known inability to cover polar regions.

In this paper, after carefully examining the pros and cons of the two connectivity solutions (ground station or GEO relay), we conclude that they are complementary rather than alternative. The aim of this paper, and its most important contribution, is thus to show that this cooperative use is possible and that the enabling technology is that of DTN and its related protocols, including CGR (Contact Graph Routing) [13].

To this end, after two introductory sections devoted to DTN and ION (the BP and CGR implementation developed by NASA) [14], [15], we study the concurrent transmission of both bulk data (e.g. images) and "streaming-like" data (e.g. telemetry) from a LEO satellite connected via both one ground station and a GEO relay. The results of a series of tests on a virtual testbed, running the GNU/Linux operating system and ION, are then presented and thoroughly analyzed.

2 A Brief Overview of the DTN Architecture

The BP DTN architecture is based on the introduction of the new "Bundle layer" [1] between Application and lower layers (usually Transport). The corresponding protocol (the BP) [2] is in charge of the transmission of "bundles" (large packets of data) between DTN nodes. The BP layer is inserted on not only source and destination, but also on some intermediate nodes, as shown in Fig. 1, thus dividing the end-to-end path into many DTN hops (three in the figure). The BP interfaces with lower layers through “Convergence Layer Adapters” (CLAs), such as those for TCP, UDP, the Licklider Transmission Protocol (LTP) [16], [17] or Saratoga [18]. In the DTN architecture, transport protocol end-to-end features are now confined to one DTN hop, while end-to-end communication through multiple DTN hops is provided by the bundle layer, which acts as a store-and-forward overlay.

2.1 DTN Overlay

In a heterogeneous network, the intermediate DTN nodes are usually chosen at the border of each homogeneous network segment (A, B and C in Fig. 1) [7]. In this way on each DTN hop it is possible to use the best suited transport protocol (or more generally, protocol stack). For example, LTP can be used on a satellite segment and TCP on terrestrial ones. In this respect, DTN recalls TCP splitting PEPs, widely used on commercial GEO systems to cope with the long RTT. In [7] it was shown that the DTN architecture, applied to GEO satellite communications, can be actually be considered as an evolution of TCP-splitting PEPs.

2.2 BP Store-and-Forward and Custody Option

The transmission of bundles is based on store-and-forward. If the link to the next “proximate” node is not available, bundles received must be locally stored even for relatively long periods of time. This is essential to cope with disruption and intermittent connectivity.

To make bundle delivery still more reliable, the custody option can be set. In this case the application on the source node asks the bundle protocol of all DTN nodes on the path to take “custody” of the bundle by setting a bit in the bundle header. A DTN node may or may not accept custody of the incoming bundle, i.e. the task of bundle retransmission and reliable delivery to another “custodian” or to destination. If it accepts, it must notify the previous custodian and store bundles on persistent memory (e.g. on hard disks), to increase robustness in case of reboots or hardware failure.

2.3 Scheduled Links and Licklider Transmission Protocol

Scheduled links allow the convergence layer to open and close connections at exactly the beginning and end of known contacts, thus maximizing link usage efficiency. They are particularly useful when contacts are short, as here between the LEO sat and the ground station. Note, however, that at present this feature is supported in ION only by the LTP convergence layer. LTP provides retransmission-based reliability over point-to-point links with extremely long RTT and/or frequent disruption, and so is suitable as DTN convergence layer in space environments [16], [17]. Here, we will use LTP on the satellite links for the following reasons: resilience to long RTTs (useful for the connection via the GEO relay), possibility of matching the available bandwidth (LTP is rate controlled), and compatibility with scheduled links and CGR. Saratoga, which could be used in alternative to LTP as in [6], has not been considered here because it has not been openly released yet.

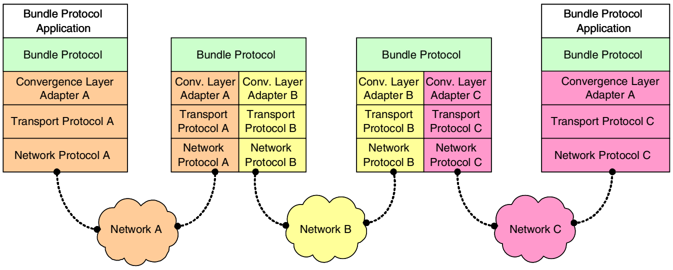

Fig. 1. DTN Bundle Protocol architecture and protocol stack

3 ION (Interplanetary Overlay Network)

ION is the DTN BP implementation developed by NASA JPL (Jet Propulsion Laboratory), with the contributions of Ohio and other Universities [14]. It is open source, available for GNU/Linux (and other platforms) [15], and is partially interoperable with DTN2, the BP reference implementation [19]. ION has been preferred here because it includes CGR, LTP and scheduled links.

3.1 Contact Graph Routing

CGR is a dynamic routing algorithm for DTN networks characterized by intermittent scheduled connectivity [13]. In these environments communication between DTN nodes is possible only during “contact windows”. Each contact offers the opportunity to transfer a limited amount of data. Its maximum is the “contact volume”, given by the product of the Tx rate and the contact window. Contact periods and Tx rates are summarized in a “contact plan”, assumed to be known a priori, because dependent on either DTN node motion or scheduled bandwidth allocation. On each node the CGR uses the information contained in the contact plan to find the most suitable path from source to destination, following a complex algorithm, which has recently been updated. The key points are the following.

- Each node implementing CGR has in principle a global knowledge of contacts; however, in practice it may be useful (as will be shown later), to eliminate superfluous information in the contact plan for a specific node.
- For each bundle, CGR computes the full route to destination and selects “the best” path; however, this only determines the most suitable “proximate” DTN node.
- The route is computed at each node implementing CGR, either at bundle creation (for the source) or at bundle arrival (for intermediate nodes).
- Routes are always recomputed for each new bundle, or in case of re-transmission, to cope with network dynamics.
- There are backoff mechanisms in case a bundle cannot be transferred because of some sort of impairment.
- Static routes may integrate CGR, but only if CGR is unable to find a route (either because no suitable contacts or no information about a node in the contact plan).

- CGR can compute route to destination for nodes included in the contact plan, while non-included nodes can be reached through gateway nodes.
- The criteria for "best" route selection may vary. In the latest ION releases the "best" path is that which provides the shortest "expected delivery time" [15].
- CGR takes bundle priorities into account.
- CGR path computation considers data already scheduled for transmission to "proximate" nodes (like seats booked on a flight), but not on successive hops. More generally, congestion control in DTN is a complex problem [20].

4 LEO Communications through a GEO Constellation and a Ground Station

In our scenario, a LEO satellite for Earth observation is connected to its control centre by two possible paths: via one ground station, or via a GEO satellite constellation, acting as a relay. The two solutions are not alternative, but complementary, as we want to show. More specifically, our aim is to prove that, thanks to the ION CGR, the two paths can be pooled and shared dynamically by different kinds of BP traffic. In particular, we will show that it is neither necessary nor advantageous to reserve one path statically for a single kind of traffic (e.g. telemetry vs. images).

4.1 DTN Topology and Protocol Stack

Our satellite communications scenario consists of five DTN nodes (Fig. 2): a LEO satellite, a ground station used by LEO, a LEO Control Centre, a GEO control centre and a final user. Note that the GEO relay is not in the figure because it is transparent to BP traffic (it is not a DTN node). Intermittent satellite links are denoted by dotted lines, terrestrial wired links by continuous ones. To cope with intermittency, the LTP convergence layer is used on both satellite links. By contrast, as terrestrial hops are continuous, the TCP convergence layer is more suitable. We consider the transfer of both telemetry data and image files. The source for both is the LEO satellite, while the destination is LEO control centre for telemetry and the final user for images.

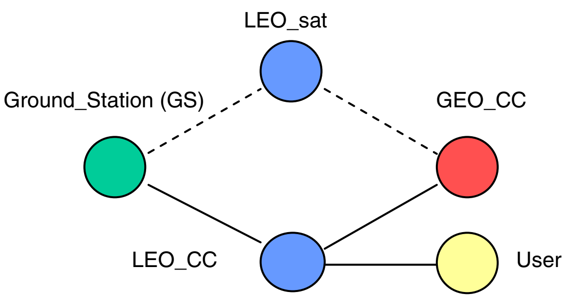

Fig. 2. Topology of the LEO-GEO scenario. Dotted lines: intermittent sat links (LTP); continuous lines: continuous terrestrial links (TCP).

4.2 Dual Characteristics of Satellite Sops: Time Availability and Bandwidth

For LEO and GEO satellites we want to adhere as closely as possible to [12]. For the LEO we consider the same orbital data (a height of 720 km and a quasi-polar sun-synchronous orbit, an orbital period of 100 min). A few integrations are however necessary, regarding the connection via the ground station, which was not considered there. We will also emphasize the duality of the two satellite hops.

LEO_sat-GEO_CC hop. In this case, the time availability is relatively high, roughly 70% of every orbital period, with two disruptions of approximately 15 min in correspondence to the poles (see Figure 7 of [12]). By contrast, the Tx rate is relatively low. We have the choice between two kinds of service. The “Standard IP” is best effort with a maximum of about 470 kb/s in each direction. However, the bandwidth is shared among all users of the same spot and, probably worse, variable in time, which could be problematic at Transport layer. The “Streaming IP”, offers fixed rates in a range from 8 to 128 kb/s. We will use it assuming a fixed rate of 128 kbit/s.

LEO_sat-GS hop. This hop has opposite characteristics. Here, we assume a ground station far from the polar regions, with a contact window of 10 min. Moreover, for the sake of simplicity, we consider just one orbital period, in which we have one contact. We also assume a Tx rate of 10 Mbit/s, thanks to the low path loss.

4.3 CGR and Contact Plans

The characteristics of DTN hops are summarized in the LEO_sat contact plan given in Table I. The first row of the table, and the following three, represent also the only contact plan information that must be provided to GEO_CC and GS, respectively. Dummy contacts (i.e. contacts longer than the experiments) have been inserted for continuous links. Finally, no information about the LEO_CC-User link is given because irrelevant for LEO_sat (all bundles to the user must be routed to LEO_CC).

Table 1. LEO_sat Contact Plan. LEO_sat Contact Plan.

Link	*Contact#*	*Start-stop time (min)*	*Speed*	*Contact Volume*
LEO_sat-GS	1	45-55	10Mbit/s	750 MB
LEO_sat-GEO_CC	1	1-20	128kbit/s	19.2 MB
	2	35-70	128kbit/s	33.6 MB
	3	85-100	128kbit/s	14.4 MB
GS–LEO_CC	Dummy (TCP cont.)	1-200	10Mbit/s	
GEO_CC-LEO_CC	Dummy (TCP cont.)	1-200	10Mbit/s	

5 Experiments

All tests were carried out on a testbed consisting of five GNU/Linux virtual machines running ION 3.0.2. The experiments are presented in ascending order of complexity. For easier test execution, while link speeds are left unaltered, actual contact durations are scaled down by a factor 60 (s instead of min), and so contact volumes.

5.1 Streaming Traffic Only (TMTC)

We start by considering the transfer of "streaming" data generated at regular intervals on board the satellite, e.g. telemetry. We assume that a new bundle of 5 kB is generated every 5m in the real world, i.e. every 5s in our experiments. These bundles have a very high priority (more than "expedited", 2.2 in ION priority settings) and should be delivered to the LEO control centre as soon as possible, either through the GEO relay or through the ground station, the faster the better. The transfer must be reliable; therefore, the custody option is set. Results are presented in Fig. 3, which gives the time series of bundle generated ("src") and delivered ("dlv via GEO"). At the bottom of the graph the LEO_sat contacts are also shown.

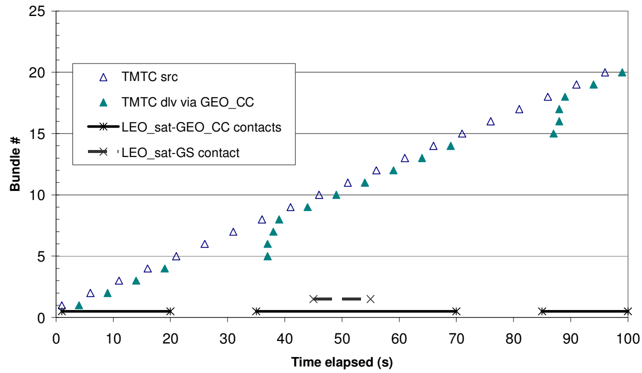

Fig. 3. Bundle Telemetry traffic (from LEO_sat to LEO_CC). Both GS and GEO links available.

At the beginning of the experiment, the LEO_sat-GEO_CC first contact is open and bundles are promptly delivered through it, as expected, until the first polar disruption occurs at 20s. Bundles generated during this disruption (bundles 5-7) cannot immediately be forwarded because there are no more contacts available. They are safely kept in custody on a local database, waiting for the next contact. After 15s the second LEO_sat-GEO_CC opens, and these bundles are promptly delivered to destination followed by new ones. Note that as the BP protocol (by contrast to TCP) does not enforce an ordered bundle delivery, waiting bundles are transmitted by LTP CL in parallel to reduce delay and to more efficiently exploit the bandwidth available.

As a result, bundles can be delivered slightly out of order (i.e. with minimal differences in delivery time). This sort of jitter is not relevant and has been deliberately filtered here, in the interest of result readability. Bundle transfer goes on regularly until the second polar disruption, and then until the end of the orbital period (100s). Note that for bundles generated during the LEO_sat-GS contact this additional path is also available, but never selected. This is because in case of parallel contacts CGR gives priority to the contact that starts first (and this even when both the contacts are already open, as here). Results show that DTN BP is able to promptly recover from disruption, as bundles generated during disruption are sent immediately after.

5.2 Data Only (Images)

We continue our analysis by considering the transfer of images data bundles from LEO_sat to User. In this case we assume that a burst of 20 bundles of 100 kB is generated during the first polar disruption, at 25s. They have low priority ("bulk", i.e. 0 in ION priority settings) and are addressed to the User node, which, however, can be reached only through LEO_CC, as before. After 5s, these bundles are followed by a high priority ("expedited", i.e. 2.1 in ION priority settings) bundle always of 100 kB, representing urgent sensor data (e.g. a high value target).

GS link only; both bulk and expedited bundles. Let us temporarily assume that the GEO relay is not present and that the only possibility is to use the LEO_sat-GS contact. Results are given in Fig. 4. All bundles are timely delivered through the LEO_sat-GS contact, which is the only one available, as soon as it opens. The relevant information for future comparisons is: the expedited bundle is delivered first, although generated last (apart from the usual jitter due to LTP parallel transfers); then, all bundles fit in this contact.

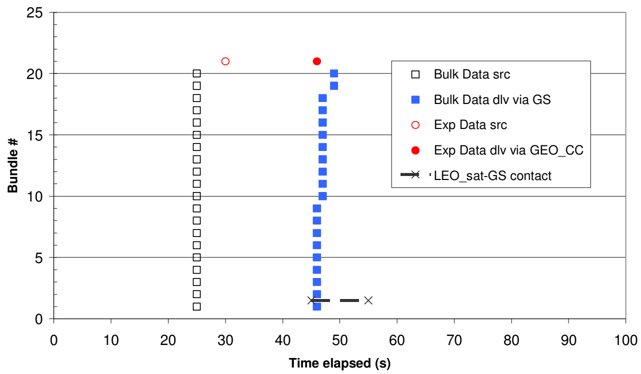

Fig. 4. Bundle Data traffic (from LEO_sat to User). GS link only; both bulk and expedited bundles.

GS and GEO links; bulk bundles only. We now re-insert the GEO-relay, so that all contacts are available again. However, we remove the expedited bundle. Results are given in Fig. 5, and are not as intuitive as before; it is necessary first to consider the peculiarities of DTN CGR routing. When a bundle is generated, CGR is invoked to find the "best" route for it, which can differ for each bundle to cope with link intermittency. To highlight this crucial point, we deliberately generated 20 bundles at the same time, addressed to the same destination, and with the same priority. Looking at results, we can see that the first 6 bundles are routed through the GEO-relay, the others through the ground station. This is due to the fact that the routing decision is taken bundle by bundle and that CGR gives priority to the contact that open first, i.e. the second LEO_sat-GEO_CC contact. However, when its residual volume has finished, this contact is no longer considered (like a "fully booked" flight), and the next bundles are routed on the next contact available, i.e. LEO_sat-GS. This very reasonable policy is however disturbed by the presence of nested contacts, as here. Although the overall result is satisfactory, as CGR has allowed the pooling of the two paths and all bundles are delivered in a reasonable time, we observe two sub-optimal results. First, the order of delivery is scrambled on a large scale (bundles 1 and 2 are delivered first; then 7-20, with 3 in parallel, finally 4-6); although this is compliant with BP rules, is not optimal. Second, bundles 4-6 could have been delivered earlier through the LEO_sat-GS contact.

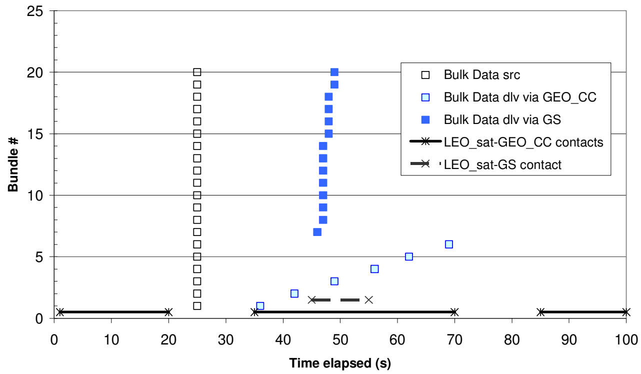

Fig. 5. Bundle Data traffic (from LEO_sat to User). Both GS and GEO links available; bulk bundles only.

Both GS and GEO links available; both bulk and expedited bundles. By re-inserting the expedited bundle into the latest scenario, we obtain the results given in Fig. 6. The good news is that the expedited bundle is delivered first, on LEO_sat-GEO_CC, although this contact was already "fully-booked" when it was routed. This positive result is expected, as CGR deliberately does not consider the volume allocated to lower priority bundles in checking the residual capacity. The bad news is that because of the insertion of the expedited bundle, bundle 6 cannot be transmitted, as it was supposed to be, before the closure of the second LEO_sat-GEO_CC contact, and must be deferred to the third, after the second polar disruption. The sub optimality here is that when CGR "overbooks" the second LEO_sat-GEO_CC contact, the LEO_sat-GS contact still has a lot of residual capacity, and bundle 6 could have been re-allocated to it. Ironically, this bundle would have arrived earlier than expected! This suggests the insertion in CGR of an "overbooking" check, with a forced re-routing of lower priority bundles waiting to be forwarded on an "overbooked" contact.

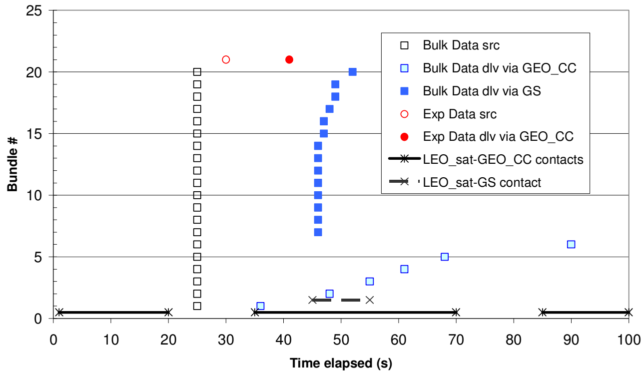

Fig. 6. Bundle data traffic (from LEO_sat to User). Both GS and GEO links available; both bulk and expedited bundles.

5.3 Telemetry and Images

In this last experiment, telemetry and images are generated in parallel, with all contacts available. Results are given in Fig. 7. The complexity of the results make it clear that the experiments presented so far were a necessary pre-requisite to the interpretation of these last results. There are few differences with respect to the merging of results for telemetry alone (Fig. 3) and images alone (Fig. 6). The most apparent is that now not only bundle 6, but bundle 5 too has also been deferred to the last contact; second, that telemetry bundle 14 has also been deferred; last, that telemetry bundle 20 is not delivered in the orbital period, but it is however delivered immediately after (not in the graph), so this last difference is of little significance. All can be explained on the basis of CGR behavior, as already discussed. The contact volume of the second LEO_sat-GEO_CC contact is allocated first to image bundles 1-6, which, however, have the lowest priority; then we have the allocation of the image expedited bundle, of higher priority; finally, we have the allocation of telemetry bundles generated during the first polar disruption and during the contact itself, with the highest priority. This double "overbooking" explains the deferred delivery of bulk bundles 5 and 6 and the deferred delivery of telemetry bundle 14, generated immediately before the closure of the contact, when LTP was already fully busy in the attempt to complete transfer of previous bundles.

From a general point of view, results are encouraging. They show that the two possible connections (via GEO relay and via ground station) can be pooled thanks to CGR (no need to reserve a path for a specific kind of traffic) and that priorities are easily enforced and generally respected. In fact, all high priority bundles are routed via GEO-relay not as a result of a fixed assignment, but because this route offers to them the fastest delivery in the scenario considered; conversely, bulk bundles can exploit the GEO-relay, but only when there is residual capacity available, otherwise are routed to the ground station.

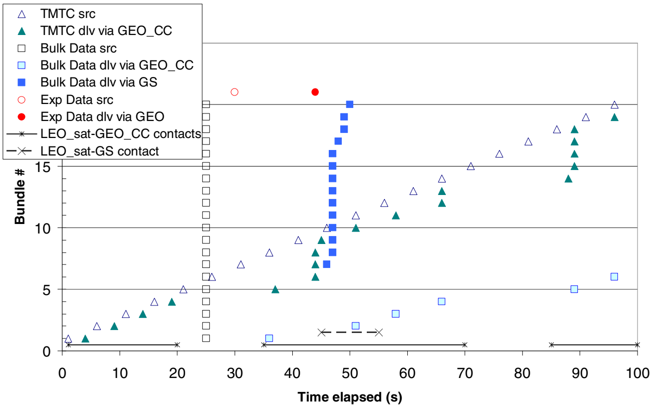

Fig. 7. Overall bundle traffic. Bundle telemetry (from LEO_sat to LEO_CC, always via GEO_CC) and Bundle data (from LEO_sat to User, either via GEO_CC or GS).

6 Conclusions

In this paper we have shown that GEO relays and ground stations complement each other and that DTN protocols and CGR routing are the enabling technology for their use in tandem. Considering the complexity of the scenario, the results are more than satisfactory. They show in particular that DTN BP is able to recover promptly from disruption, present on both satellite links, and that CGR allows different kinds of traffic, with different priorities, to share the paths dynamically, thus avoiding any fixed assignment. The comments to the results suggest some possible improvements to CGR congestion control. They also provide a comprehensive explanation of why the features peculiar to DTN so greatly contribute to the positive results achieved.

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