Energy-aware routing algorithm for DTN-Nanosatellite networks

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***Abstract*—Satellite constellations are envisioned as meaningful transport networks to forward data throughout the world. Low Earth Orbit (LEO) satellites are the most appealing for this purpose due to their low altitude which allows guaranteeing certain performance, especially in terms of delivery time. Mega-constellation of small LEO satellites (micro- and nano-satellites) are planned to be employed to cover the entire Earth's surface. However, these satellites have several constraints which affect the data forwarding process and have to be taken into account. Energy is one of these constrained resources. Energy storage and recharge are limited by the reduced battery capacity and solar panel surface area, while telecommunication hardware energy consumption is considerable especially in case of high traffic volumes. In this paper, we propose a novel energy-aware routing algorithm based on the Contact Graph Routing (CGR) called E-CGR. E-CGR exploits static and known a priori information about contacts (begin times, end times, and overall contact volumes) to compute complete routing paths from source to destination which are then validated and confirmed from the energy viewpoint.**

I. Introduction

Satellites are no longer just big and very expensive objects, new classes of small satellites, called micro-, nano-, and pico-satellites, are increasingly catching our attention [1]. Their size and, consequently, cost are decreasing, allowing more entities to gain access to space. These small LEO satellites are mainly designed for specific and short-term missions and are appealing due to their low cost and fast design time. Another interesting aspect is the foreseen integration between satellite networks and terrestrial infrastructures as part of an overall communication network in the forthcoming next generation of mobile communications (5G). Pursuing this opportunity, some industries are studying and planning the deployment of swarms or constellations of small satellites for specific application scenarios. For example, Eutelsat is planning to deploy a LEO nanosatellite constellation called Eutelsat LEO for Objects (ELO) dedicated to Internet of Things (IoT) applications [2]. In this futuristic and realistic vision, satellites will forward data from one area to another acting as "routers in space", helping increase coverage, reliability, and availability, some of the 5G Key Performance Indicators (KPIs) [3]. However, there are several constraints which affect satellites more than terrestrial routers and are stricter as the size decreases, such as storage capacity and available energy. Employing energy-aware communication strategies is crucial to increase satellite communication network throughput and satellite lifetime [4].

Data transmission and reception require an amount of energy which considerably impacts the satellite energy budget. In small satellite networks, satellites may not be able to transmit data for certain time periods. As a consequence, possible routing paths between source and destination may include satellite links which are not all active at the same time. This causes the need for each nanosatellite to store data in its buffer for long time periods, which can be solved by applying the Delay and Disruption Tolerant Networking paradigm (DTN) [5]. The DTN paradigm deals with link disruptions and long delays, allowing nodes (both ground stations and satellites) to store data until the next contact is available. However, having reduced size and weight, nanosatellites tend to have a limited capacity of energy storage and recharge compared to standard Low Earth Orbit (LEO) satellites, which can hinder them from transmitting the stored data for long time periods. Smart routing strategies which help reduce data delivery time and take into consideration the strict resource constraints are crucial to allow users to receive data respecting Quality of Service (QoS) requirements.

We propose an energy-aware routing algorithm for DTN-Nanosatellite networks in order to allow nanosatellites to preserve energy and function continuously with an increment in performance. Our algorithm, called E-CGR, is based on the Contact Graph Routing (CGR) algorithm [6], widely employed in DTN networks where there is an a priori knowledge about future contacts among nodes, as in satellite networks [7]. E-CGR allows satellites to upload data packets only if they will be able to download them to their next hops, i.e. the estimated values of satellite available energy in the time instant when they have to forward the data are greater than the energy required for the transmission.

The paper is structured as follows: possible solutions to the routing challenge in satellite networks focusing on energy aspects and DTN paradigm are provided in Section II. The considered satellite energy model is described in Section III, followed by the detailed description of the proposed energy-aware routing algorithm (E-CGR) in Section IV. The performance analysis to quantify and highlight the improved performance of E-CGR compared to the standard CGR is reported in Section V. Conclusions are drawn in Section VI.

II. Related works

A. Energy-efficient routing in satellite networks

Energy efficiency is a crucial aspect to consider in the design of routing strategies for satellite communication networks. Several studies have already been performed with this aim. Authors in [8] analyse the problem of energy-efficient satellite routing proposing a satellite power model and three routing algorithms. They focus on prolonging satellite lifetime by minimizing the battery recharge/discharge cycle number and exploiting node sleep mode strategies. A method based on Multi-power Level Multi-Transmission (MLMT) Space-Time Graph is proposed in [9] to reduce energy consumption for broadcast communications: a heuristic algorithm finds an energy-efficient path through the graph from the start time of the broadcast to the given deadline, which covers as many nodes as possible. [10] proposes an online control algorithm, called EESE, that minimizes the overall energy consumption over time in a network composed of a satellite swarm with Inter-Satellite Links (ISLs) and terrestrial terminal stations, opportunely redirecting traffic through different satellite-ground links. Energy-efficiency in nanosatellite networks is investigated in [11], where the authors propose a multiple hopping relay methodology to deliver scientific data to ground terminals with the optimal energy balance of the entire network.

However, none of these proposed solutions have been developed for DTN-satellite networks and none of them consider the possible case in which satellites do not have enough energy to send data packets through the computed routing path.

B. Routing in DTN-satellite networks

Routing issues in DTN networks involve additional variables compared to "classical" networks. The topology is not constant during all network lifetime and the links may change their state over time. The objective of "classical" routing algorithms is to find the best currently-available path to move traffic end-to-end, but in DTN networks an end-to-end path may be permanently unavailable. To allow data exchange, DTN nodes can store data packets in their buffers for a much longer time compared to terrestrial routers by employing long-term storage. The DTN routing problem is a constrained optimization problem where single links may be unavailable for long times and with resource constraints at each node. In a DTN-satellite network, satellites change their positions in a predictable way. Information about contact start times and durations is known a priori, which eases the development of possible solutions. When changes in connectivity are planned and scheduled, one of the most used routing algorithms is the Contact Graph Routing (CGR) [6]. Contact information is stored in a list called "Contact Plan" and is exploited to compute routing decisions for each single packet, called bundle, by intermediate nodes. Extensions have been developed and proposed to enhance the standard CGR, as well as to prove its reliability in LEO satellite communication networks [12]–[14].

We performed similar studies related to routing in DTN-Nanosatellite networks in [15], [16], and references therein. In these studies, we focused our attention on the bundle delivery time reduction considering the known a priori contact information and the strict limitation of nanosatellite buffer storage. In this paper, we also consider the limitation of nanosatellite available energy and the energy consumption due to data transmission and reception. To the best of our knowledge, current CGR extensions do not consider node available energy as a variable which can affect the obtained performance and the routing path computation.

III. Satellite energy model

Before describing in depth the E-CGR algorithm, we'll briefly look at the energy system and model of current satellites in order to understand how our algorithm estimates the satellite available energy values. The Satellite Electrical Power System (EPS) is composed of a board whose aim is to distribute the available energy, gathered by solar panels and stored in a battery, to all satellite subsystems [17]. Most small satellites are only powered by solar energy. The average generated power ranges from a few to a few tens of Watts due to the reduced size of the external structure. This value can be increased by using deployable solar panels [18]. Typical low orbits expose satellites to the Sun for about 2/3 of their 90-105 minute duration. Satellites need to be able to store enough energy to remain powered on even when they are in the shadow of the Earth (eclipse periods).

The energy consumption due to data transmission per bit is modelled through the metric Energy per bit E_t [19], defined as:

$$E_t = P_t \cdot t_b + P_c \cdot t_b = \\ = \frac{\left(2^{\frac{1}{W \cdot t_b}} - 1\right) \cdot W \cdot N_0}{d^2} \cdot t_b + P_c \cdot t_b \tag{1}$$

where P_t is the transmission power, t_b the time to transmit one bit, P_c the average circuit power, W the channel bandwidth, N_0 the noise spectral density, and d the distance between transmitter and receiver.

The power consumed by the transceiver when it is on P_o is set to a constant, as well as the energy consumption due to data reception per bit E_r. We assume satellite transceivers are active only when satellites are in contact with ground stations, i.e. they are turned off when no planned contacts are ongoing.

The output power of solar panel P_s can be modelled as in [8]:

$$P_s = \eta \cdot \gamma \cdot A \cdot \cos \alpha \tag{2}$$

where η is the energy conversion efficiency, γ the amount of solar irradiance per unit area, A the area of the solar panels, and α the angle between the normal vector of the solar panel and the sunlight.

Satellite battery is recharged to its maximum capacity C only when the satellite is in sunlight periods. Eclipse periods are identified by the angle θ_o, also from [8]:

$$\theta_o(\beta) = \begin{cases} 0, \text{ if } \beta \geq \arcsin\left(\frac{R}{R+h}\right) \\ \arcsin\left[\frac{R^2 \cdot \cos^2\beta - (2Rh + h^2)\cdot \sin^2\beta}{(R+H)\cdot \cos\beta}\right], \text{ otherwise} \end{cases} \quad (3)$$

where β is the angle between sunlight and satellite orbital plane. β is not fixed and can be computed through Eq. (5) in [8]. R is the mean radius of the Earth, and h the satellite altitude.

The satellite is in the shadow of the Earth when $-\theta_o \leq \theta \leq \theta_o$, so the sunlight period duration per orbit is $(1-\theta_o \backslash \pi)\cdot T_O$, where T_O is the orbit time.

IV. Energy-aware routing algorithm E-CGR

E-CGR applies energy-efficient routing algorithm principles to the standard CGR algorithm, enabling energy-awareness in ground stations.

When a source ground station GS_{G_S} receives a data bundle B from a ground terminal GT_{T_S} to send through satellite links, it computes a possible routing path applying the standard CGR, in order to find the path which minimizes B's delivery time. GS_{G_S} keeps B stored in its buffer until the next communication opportunity with the identified next hop (satellite SAT_S) takes place. When a contact between GS_{G_S} and SAT_S starts, SAT_S sends a defined bundle, called energy bundle, in order to make GS_{G_S} aware of its current energy level. In particular, satellite energy bundles contain information about satellite current available energy and amount of data stored in the buffer and waiting to be forwarded to ground stations. GS_{G_S} exploits this information to verify if B's previously computed routing path through SAT_S is usable, i.e. if SAT_S's available energy when it enters in contact with B's destination ground station GS_{G_D} is enough to guarantee B's transmission. To perform this action, GS_{G_S} estimates the value of SAT_S's available energy in the time instant $t_{tx}^{G_D}$ when B should be forwarded to GS_{G_D} as:

$$\begin{aligned} E_a(S, t_{tx}^{G_D}) =& E_a(S, t_n) + P_s \cdot D_L - \\ & - \sum_{j=1}^{N_S}\left[(V_j \cdot E_r + P_o \cdot D_j + (Q_j^S + Q_E)\cdot E_t\right] \end{aligned} \quad (4)$$

where t_n is the current time instant, D_L the duration of the sunlight periods between t_n and $t_{tx}^{G_D}$, N_S the number of SAT_S's contacts between t_n and $t_{tx}^{G_D}$, V_j the contact volume of the j^{th} contact, i.e. the maximum amount of data that can be exchanged in the j^{th} contact, D_j the duration of the j^{th} contact, Q_j^S the amount of data SAT_S has to send during the j^{th} contact, and Q_E the size of the energy bundles.

In this way, GS_{G_S} estimates the future value of SAT_S available energy starting from the value contained in the received energy bundle ($E_a(S, t_n)$) and considering the amounts of recharged and discharged energy until B's transmission to GS_{G_D}. Since the exact amount of data that satellites will upload during each future contact cannot be known, we decided to consider the worst case, i.e. they receive the maximum amount of data for these contacts (contact volumes).

Finally, the transmission of B is allowed only after GS_{G_S} has checked if SAT_S will be able to send all the data bundles already stored in its buffer through all the planned contacts, i.e. if:

$$E_a(S, t_{tx}^g) \geq \begin{cases} Q_{S\to g}\cdot E_t \quad g = 1,\dots,nGSs \quad g \neq G_D \\ (Q_{S\to G_D} + Q_B)\cdot E_t \end{cases} \quad (5)$$

where $nGSs$ is the number of ground stations in the network, $Q_{S\to g}$ the amount of data stored in SAT_S's buffer and destined to GS_g, and Q_B the size of data bundle B.

If all tests are positively verified, GS_{G_S} sends B, otherwise re-calculates another routing path.

V. Performance Analysis

The performance evaluation has been performed considering the application scenario shown in Figure 1 and composed of a multi-orbit nanosatellite constellation and a set of terrestrial areas with one Ground Station (GS) and a set of Ground Terminals (GTs) per area. GSs, on one hand, collect/deliver data from/to the GTs located in the covered areas, and, on the other hand, send/receive data to/from the nanosatellite constellation. In the considered scenario, the GTs located in a terrestrial area can communicate with other GTs located in different areas only through the constellation and satellites (SATs) can only communicate with GSs, i.e. there are no ISLs. In this way, SATs act as "data mule", uploading data from source GS and keeping them stored in the buffer until the contact with destination GS starts, as expected in the DTN paradigm.

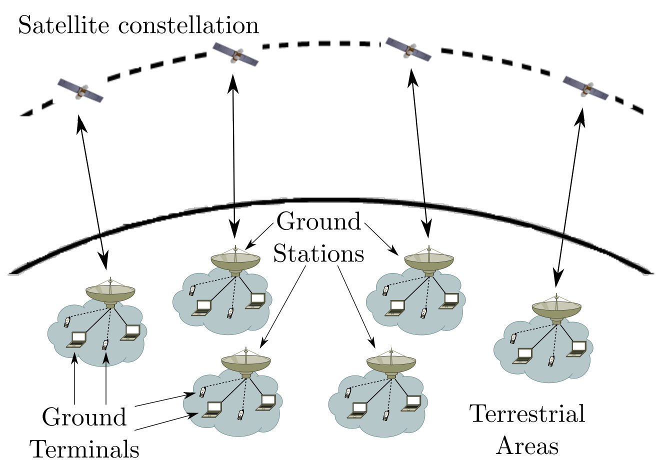


Fig. 1: Nanosatellite constellation application scenario

A module for Network Simulator 3 (NS3) has been developed (it is described in detail in [16]). It includes:

- **a Scenario module**, which allows simulating a different scenario by changing network topology parameters, such as the number and position of GS and the number of GT per area, and channel parameters, such as the satellite and terrestrial link bandwidth;

- **a DTN module**, which implements the characteristics of the DTN paradigm needed to perform a communication in this DTN-Nanosatellite network. It includes a store and forward mechanism, a personalized and light version of the Bundle Protocol [20], and the E-CGR algorithm;
- **a LEO nanosatellite constellation module**, which allows defining a different LEO satellite constellation by changing the number of satellites and orbital planes, the orbital plane parameters, and satellite design parameters, such as the satellite battery capacity and solar panel surface area. During the simulations, this module updates the position of each nanosatellite in order to simulate real satellite tracks.

The simulator allows setting the position of ground stations and the initial position of nanosatellites in a 3-D space. Ground station positions are set in Latitude, Longitude, and Altitude (LLA) coordinates, whilst nanosatellite positions are computed and updated by using the widespread orbital model called NORAD SGP4 [21]. In the simulated scenario, 120 nanosatellites are equally distributed among 10 circular orbits and equally spaced within each orbit. Traffic flows are generated by the GTs of each area, following a Poisson distribution with an inter-bundle generation time T_i, and destined to other GTs located in a different area. In this way, all data bundles have to be forwarded through the nanosatellite constellation to be delivered to their destination GTs.

Two sets of simulations has been performed: in the first one, the number of GTs per terrestrial area $nGTs$ is constant and set to 1000 and the number of GSs $nGSs$ is increased. In the second one, we do the opposite, changing $nGTs$ and keeping $nGSs$ constant to 100, in order to stress the network with different traffic flow configuration cases increasing the number of traffic flows and, consequently, the traffic volume. The ground station coordinates have been set in order to uniformly distribute the ground stations throughout the Earth's surface.

The numerical values of nanosatellite constellation, satellite design, satellite orbital plane, satellite links, and traffic flow configuration parameters are summarized in Table I.

For the sake of completeness, we set α to 30° in order to simulate an imperfect alignment between solar panel and Sun, which is common considering the simple attitude control systems of small satellites, and β to 40°. β can be set to a constant due to the relatively short simulation time that has been chosen.

The results obtained by using E-CGR and standard CGR are compared through two performance metrics: the Average Delivery Time (ADT) and the Percentage of Delivered Bundles (PDB).

ADT is defined as:

$$ADT = \frac{\sum_{b=1}^{M} \left(T_b^{RX} - T_b^{TX}\right)}{M} \quad (6)$$

where M is the total number of generated data bundles and T_b^{TX} and T_b^{RX} the time instants when the b^{th} data bundle is sent by the source GT and is received by the destination GT, respectively.

TABLE I: Simulated scenario design parameters

Orbital planes eccentricity	0
Satellites altitude h	600 *km*
Orbital planes inclination i	88°
Orbital planes argument of perigee	90°
Minimum Elevation angle between GS and SAT for transmissions	20°
Data bundle size	1 *kB*
Energy bundle size	$(nGSs+1)\cdot 4$ *B*
Satellite channel bandwidth W	50 *MHz*
Time to transmit one bit t_b	20 *ns*
Solar panel energy conversion efficiency η	0.19
Solar irradiance per unit area γ	1353 W/m^2
Solar panel surface area A	500 cm^2
Angle between solar panel normal vector and the Sun α	30°
Mean Earth radius R	6371 *km*
Maximum satellite battery capacity C	40 *Wh*
Inter-bundle generation time T_i	300 *s*
Simulation Duration	24 *hr*

The obtained results are shown in Figure 2 and highlight a performance improvement that raises up to 31% by increasing $nGSs$ and to 35% by increasing $nGTs$.

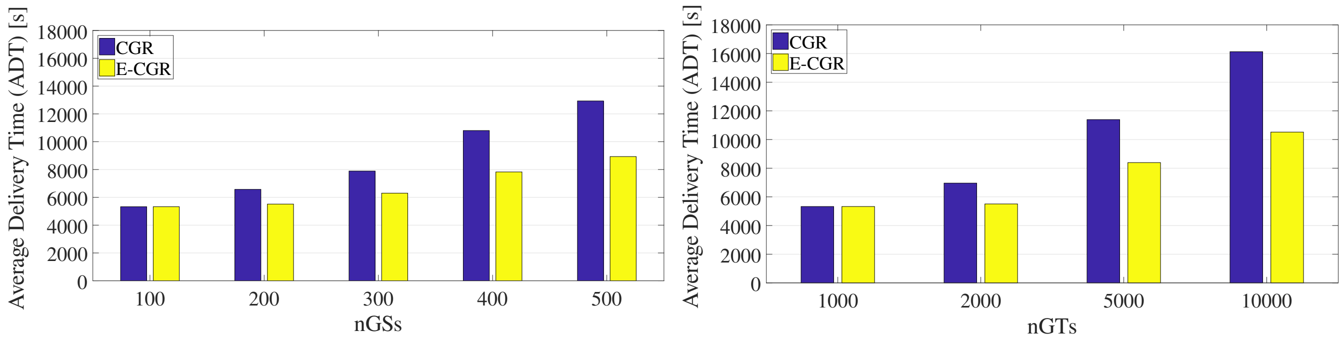
By using standard CGR, satellites may not be able to download data bundles when they enter in contact with the destination GSs due to the low energy level. Higher the data traffic volume, higher the satellite energy consumption, and worse the effect of this phenomenon. Consequently, some satellites have to keep these data bundles stored in their buffer waiting for the next available contacts, wasting satellite buffer capacity and increasing the bundle delivery time.

To better quantify this problem, the obtained Percentage of Delivered Bundles (PDB) from the beginning to the end of the simulation is shown in Figure 3.

The number of bundles that have not been delivered by the end of the simulation with the standard CGR is considerable, up to 17% by increasing $nGSs$ and up to 27% by increasing $nGTs$. These percentage are reduced, respectively, to 10% and 17% by using E-CGR.

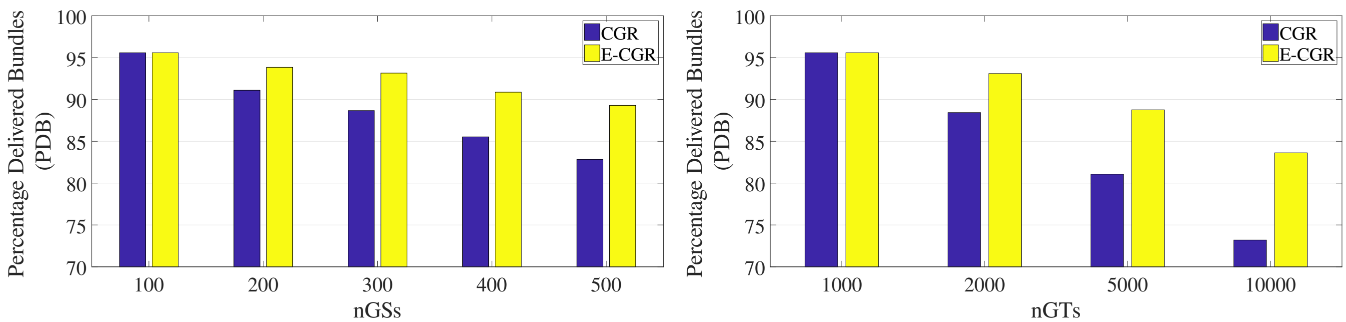
VI. Conclusions

Nanosatellites suffer from strict resource constraints and limited communication opportunities with ground stations due to their size and weight limitations and low altitude orbit. Available energy is one of the parameters which should be considered and properly managed to guarantee a certain



(a) (b)

Fig. 2: ADT obtained by using CGR and E-CGR changing $nGSs$ (a) and $nGTs$ (b)



(a) (b)

Fig. 3: PRDB obtained by using CGR and E-CGR changing $nGSs$ (a) and $nGTs$ (b)

throughput and delivery time for a nanosatellite communication network and to avoid possible situations where nanosatellites are not able to download data due to their low energy level.

In this paper, we propose an energy-aware routing algorithm for DTN-Nanosatellite networks called E-CGR. Its aim is to make ground stations aware of nanosatellites' available energy in order to send data only when nanosatellites will have enough energy to carry out the forwarding.

The obtained results of E-CGR algorithm show a decrease of the average data delivery time and an increase of the amount of data bundles delivered to their destinations with respect to the classical CGR.

A further improvement of the resource management can be obtained by considering and modelling all the variables which can affect the routing process in this kind of networks, especially the constrained ones such as the nanosatellite buffer occupancy, in order to define a complete routing algorithm.

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