Design Challenges in Contact Plans for Disruption-Tolerant Satellite Networks

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ABSTRACT

During the past 20 years, space communications technologies have shown limited progress in comparison to Internet-based networks on Earth. However, a brand new working group of the IETF with focus on DTN promises to extend today's Internet boundaries to embrace disruptive communications such as those seen in space networks. Nevertheless, several challenges need to be overcome before operative DTNs can be deployed in orbit. We analyze the state of the art of effective design, planning, and implementation of the forthcoming network communications opportunities (contacts). To this end, different modeling techniques, system constraints, selection criteria, and methods are reviewed and compared. Finally, we discuss the increasing complexity of considering routing and traffic information to enrich the planning procedure, yielding the need to implement a contact plan computation element to support space DTN operation.

INTRODUCTION

The Internet has enabled seamless, transparent, and heterogeneous communication, migrating centralized functions toward scalable and efficient distributed systems such as modern banking or education platforms. Back in the 1960s, the concept of the Internet grew out of military studies on how to build robust networks. As a result, addressing and routing were decentralized; but most important, the primary purpose of the network was to remain connected beyond any catastrophe. Unknowingly, the Internet inherited an *end-to-end connectivity* paradigm that shaped modern networked communications including the popular TCP/IP protocol stack. In this context, and under different orbital environments, satellite networks intended not to be the exception.

Traditional geostationary Earth orbit (GEO) satellite relay systems implement bent-pipe repeaters to transmit from one location on Earth to the satellite and back to another location on Earth. Therefore, GEO relays are appealing for broadcasting information to a large geographical area; however, when considered for bidirectional and interactive data communication, challenges such as long round-trip times (RTTs) and frequent channel disruptions must be addressed. This effect is even more dramatic in deep space (DS) systems as longer distances provoke higher delays and severe disruptions due to planet rotation, making permanent and conversational Internet-like communications infeasible [1]. For example, TCP simply cannot tolerate the 20-min propagation time a signal might take from Earth to Mars. On the other hand, disruptions are the prevalent effect in low Earth orbit (LEO) satellite systems. In order to provide voice services, an Iridium satellite constellation system had to be designed to sustain stable end-to-end multihop paths in a highly dynamic and extensive topology. To this end, connectivity was achieved at the expense of a highly complex, expensive, and controversial system. Most recently, the ambitious Defense Advanced Research Projects Agency (DARPA) F6 distributed spacecraft architecture project, which aimed at deploying an Internet-like mesh LEO network, was canceled due to significant increase in budget and overall complexity.

Whether by system complexity and cost in LEO, or physical infeasibility in GEO and DS systems, the end-to-end connectivity paradigm has proven to be hard to adapt to the space environment. In this context, TCP/IP-based Internet will always impose a frontier on networks challenged by delay or disruption, commonly known as delay or disruption tolerant networks (DTNs) [2]. DTN for space applications has been under discussion at the core of the Consultative Committee for Space Data Systems (CCSDS) alongside Internet standards during the past 20 years. Still, the recent formation of a DTN Working Group (DTNWG) in the Internet Engineering Task Force (IETF) might relax the original end-to-end connectivity axiom, allowing DTN applications to finally be embraced by the Internet architecture with all the benefits it entails.

In this scenario, Internet data would be routed through network nodes not necessarily having end-to-end connectivity with the final destination. Indeed, connectivity among nodes (i.e., contacts) could be sporadic but predictable due to orbital mechanics. Nodes would then store and carry these data until forwarding opportuni-

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In contrast to most terrestrial applications, space-oriented DTN behavior can be predicted in advance, enabling unique network planning and design opportunities further discussed below.

ties (contacts) are available. Since not all feasible contacts may be required to route data, previous works have investigated topology design issues related to providing connectivity among nodes at the lowest cost (e.g., minimum number of contacts) considering the time-evolving nature of the contact topology [3]. However, resource constraints (available transponders, power consumption, etc.) also need to be considered in the selection of these contacts. Besides connectivity, other criteria related to capacity and fairness are also required to select those contacts that, still satisfying a given set of constraints, can provide the best operational performance. We refer to this problem as contact plan design (CPD), where the contact plan (CP) is the resulting set of contacts that complies with restrictions and maximizes some performance metrics. Among the challenges that need to be addressed before DTN services can be fully implemented, the design of CPs is a critical problem since satellite networks have limited resources (transponders, power, fuel, etc.), which have to be considered. Recently, the design of CPs with resource constraints was proposed and investigated in [4].

In this article, we provide a detailed description of the CPD problem, and a comparison of the performance and complexity of existing solutions. In the next section we provide an overview of the DTN architecture in the space environment and discuss the CPD problem following that. Next we bring an example network under the design process to illustrate the benefits and drawbacks of the proposed CPD mechanisms. Finally, we conclude our work and set future work directions.

DTN OVERVIEW

Delay or disruption tolerant networks have received much attention during the past few years as they have been proposed for several environments where communications can be challenged by latency, bandwidth, errors, or stability issues [2]. Originally studied to develop an architecture for the interplanetary Internet (IPN) [1], DTNs have also been recognized as an alternative solution for building future satellite applications [5]; in particular, to cope with typical intermittent channels of LEO constellation systems [6]. Furthermore, DTNs have also been considered for underwater sensor networks, battlefield networks, unmanned aerial vehicle (UAV) communications systems, and connectivity in developing areas, among others.

DTNs overcome the problem of channel delays and disruptions by using a store-carry-forward message scheme. This is analogous to postal systems where messages are stored in a given place (node) until able to move (forward) to another one before reaching its final destination. Internet nodes are designed with little memory (buffer) since they can likely deliver data to the next hop after a routing decision has been made; however, DTN nodes require persistent storage as the link to the next hop might not be available for a long time. As a consequence, Internet communications can be seen as a particular case of DTN with insignificant delay or disruptions.

Among the efforts to implement practical DTNs, the definition of a new communication protocol that does not assume end-to-end connectivity between source and destination nodes has been addressed by the specification of the Bundle protocol in RFC 5050, also resulting in the availability of several software implementations of the protocol, NASA's Interplanetary Overlay Network (ION) [7] being the most popular for space-borne applications. ION was one of the first DTN-capable protocol stacks successfully tested in space in the DINET mission [8]. In contrast to most terrestrial applications, space-oriented DTNs' behavior can be predicted in advance, enabling unique network planning and design opportunities further discussed below.

DTN FOR SATELLITE NETWORKS

Technology advances, electronic miniaturization, and the industry of smaller launchers are enabling new business cases for cubesats projects like QB50, EDSN, PlanetLab, and even small-satellite companies like SkyBox (recently acquired by Google) to deploy large LEO constellations systems in the next few years. Therefore, LEO constellations promise to become the first large-scale networks to shift the current monolithic paradigm to a more efficient, scalable, and distributed Internet-like approach. Instead of continuous end-to-end connectivity, DTN would provide these constellations with an effective way to transport data in a store-carry-forward fashion not only by Earth-satellite links (ESLs) but also via sporadic inter-satellite links (ISLs). However, given the degree of conservatism in the traditional space industry, research effort is mandatory as DTNs must still go under severe scrutiny before being considered for large-scale deployments.

In particular, LEO systems are challenged by channel disruptions rather than by propagation times, which are similar to the delays experienced on TCP/IP Internet applications. However, in contrast to the Internet, space-borne DTNs' behavior is under management of a mission operation and control (MOC) center that can deterministically predict (by means of orbital mechanics and communications models) the expected contacts among nodes. Indeed, a contact can be defined as the opportunity to establish a temporal communication link among two DTN nodes when physical requirements are met (antenna pointing, received power, etc.). Henceforth, ISLs are solely thought of as point-to-point, disregarding shared medium access schemes, which fail to perform properly in extensive networks as they assume physical adjacency of many nodes. The latter is either unlikely in a free-flying constellation or demands strict flight-formation requirements to the satellite attitude and orbital control system (AOCS). Furthermore, DTN architecture can handle routing on higher layers, enabling simpler communications architectures, especially if mission requirements can be met in a disruptive scenario.

Figure 1a illustrates the concept of contact with a 4-polar-orbit-satellite (98 inclination angle and 650 km height each) DTN example network we use throughout this article. This scenario is of particular interest for Earth observation missions as satellites account for maximum distance in populated areas while approaching each other in the poles. In these areas, contacts become feasible between adjacent spacecrafts, producing a train-like formation where two directive point-to-point antennas (placed in front and back) can optimize the link budget, producing longer contacts. Henceforth, the network iterates among these contacts, but for the sake of simplicity we base further analysis solely on the half-orbit topology interval. Furthermore, contacts with ground stations are disregarded on the example, but should be transparently considered as another node with which to communicate.

The set of all feasible contacts within a topology interval in a given DTN network can be defined as the *contact topology*. However, it is possible that conflicts or constraints (interference, power restrictions, etc.) need to be addressed before committing the set of planned contacts to the network. As a result, the set of forthcoming contacts to be finally implemented in the network can be defined as the *contact plan* (CP), which is a subset of the original contact topology [9]. Henceforth, the process of selecting the definitive contact set is referred to as *contact plan design* (CPD). As it is typically assumed that all potential contacts between DTN nodes can belong to the CP, the design of CPs has thus far received little attention. However, this problem quickly becomes nontrivial in large-scale systems, and detrimental for resource-constrained scenarios such as satellite missions. Therefore, applying efficient CPD procedures can significantly improve the performance of large DTN satellite constellations.

THE CONTACT TOPOLOGY MODEL

In order to tackle the contact plan design problem, a topology modeling technique needs to be specified. Consider the four-satellite network example shown in Fig. 1a. The time evolving nature of these contacts can be captured by means of graphs, with vertex and edges symbolizing nodes and links, respectively. In other words, this representation can be thought of as a finite state machine (FSM) where each state is characterized by a graph with arcs, in turn, that represent a communication opportunity during a period of time (i.e., a contact). Each state can be identified by $k = 1, 2, \ldots, K$ conforming K graphs comprising the same set of nodes but different arcs among them. Particularly, in the suggested scenario, three states can describe the contact topology, which represents the communications evolution during half an orbit topology interval. The FSM model of the example network is illustrated in Fig. 1b.

In particular, a contact topology consists of $p_{k,i,j}$ links between nodes i and j at state k, where $p_{k,i,j}$ may adopt an integer identifying the communication interface (antenna). If no contact is feasible, $p_{k,i,j} = 0$, while $p_{k,i,j} = a$ if the contact among i and j is possible through interface a. Furthermore, at state $k = 1$, $p_{1,2,3} = p_{1,3,2} = 0$ since no physical link exists between N_2 and N_3. In general, the contact topology can be defined by a three-dimensional physical adjacency matrix, from which the contact plan can be designed by removing $p_{k,i,j}$ edges.

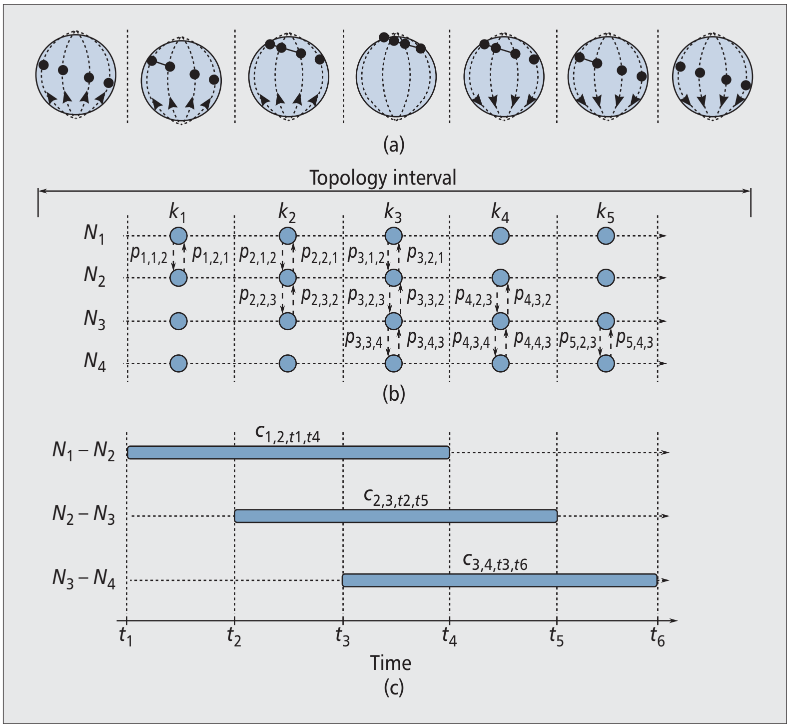

Figure 1. a) Example of a DTN satellite network modeled with b) FSM; c) CL.

Alternatively, a topology can be represented by a contact list (CL) where each contact is in the form of source, destination, start time, and stop time (as in $C_{1,2,t1,t4}$). Therefore, the example network basically consists of three contacts: N_1 to N_2 from t_1 to t_4, N_2 to N_3 from t_2 to t_3, and N_3 to N_4 from t_1 to t_4. The CL modeling for the example topology, illustrated in Fig. 1 c, is more compact than the FSM since it can be expressed as a contact table instead of an adjacency matrix. As a result, CL is the format adopted by ION [7] DTN stack implementation for CP distribution and storage. However, for CP design and engineering, the FSM model granularity might turn out to be convenient to work with, especially when applying mixed integer linear programming (MILP) optimization techniques [9]. Furthermore, as we do in the next section, the FSM model can benefit from discrete state fractionation in order to provide a more detailed and precise topology description. No matter which modeling technique is chosen, translation between FSM and CL is straightforward.

CONTACT PLAN DESIGN

In the initial phase, communications subsystem attributes, including transmission power, modulation, bit error rate, and so on, and orbital dynamics such as position, range, and attitude (orientation of the spacecraft and antenna in the inertial system) can be used to determine the feasibility of future contacts that will form the aforementioned contact topology. This technique is no different from how single-spacecraft missions currently determine space-to-earth contact

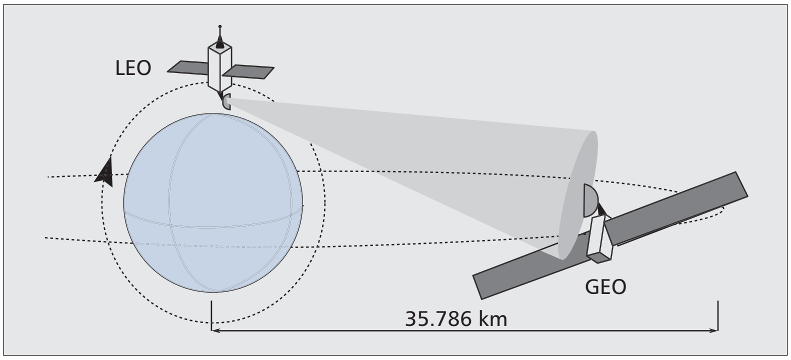

Figure 2. Interference to GEO ssatellites.

opportunities. Nevertheless, the contact topology at this stage does not necessarily encompass all system restrictions or constraints. For instance, interference generated to and from other space assets can turn a given contact unfeasible. In addition, a node may have potential contacts with more than one node at a given time but be limited to only make use of one of these opportunities due to conflicting resources. These conflicts comprise node power budgets or architectural limitations typically found on spacecraft operating in the harsh space environment. As a consequence, further work is required to design a contact plan that considers these scenarios. Finally, once the contact plan is designed, it has to be distributed throughout the network to let nodes execute the contacts as planned. The frequency and mechanisms of contact plan distribution, as well as the topology interval length, are topology-dependent and remain an open research topic.

DESIGN CONSTRAINTS

In general, we can classify the contact topology constraints in two groups: one representing those that render a particular contact (in a given timeframe) infeasible, and another that limits the number of contacts a DTN node can simultaneously support. We name the former *time-zone constraints* (TZCs) and the latter *concurrent-resources constraints* (CRCs), where both can relate not only to communications but to general system operations issues.

Time-zone constraints: In general, TZCs are those that can forbid communications in a specific geographical area or time for interference or other agency-specific reasons. As LEO constellations systems basically orbit over a wide area of Earth regions, complying with international regulations can be challenging. Moreover, as shown in Fig. 2, since ISLs in LEO constellations are held tangentially in respect to the Earth surface, GEO satellites can be interfered when LEO nodes orbit in the pole area. In particular, some GEO satellites are to be specially considered as they support manned mission communications such as the International Space Station. As a consequence, a proper irradiation policy must be considered not to generate (or receive) interference beyond the International Telecommunication Union (ITU) normative [10].

Furthermore, many other agency-specific reasons might exist for irradiating in a particular geographical area. This can be addressed by time and zone constraints that prevent the availability of a contact in the corresponding CP in a given interval. It should be noticed that these strategies can be considered as the network tolerates disruption, while systems like Iridium have had to request a complete band allocation to sustain interference-free end-to-end communications.

In general, TZCs can be applied directly to the contact topology structure by disabling the conflicting contacts. For instance, if considering the unlikely interference from the short-range antennas of the example topology, contacts from the k_3 state in the FSM model could just be removed. However, interference is not only measured in signal energy, but also in the percentage of time it reaches the interfered-with node [10]. Also, satellites might exhibit energy constraints limiting the fraction of time a transponder can be used. Therefore, there is the possibility to select which contact to disable and when, derived in a combinatorial problem similar to those found on CRC constraints.

Concurrent-Resources Constraints — CRCs are not as straightforward as TZCs as they usually involve the spacecraft architecture and resources. They end up defining the quantity of simultaneous communications (i.e., contacts) a DTN node is able to establish. Consider the architectures of Fig. 3 that apply to the example topology. In Fig. 3a, a simple power splitter divides the transponder signal energy to the two antennas of the spacecraft, while in Fig. 3b a power switch concentrates all the power in one of the available antennas. In either of the aforementioned architectures, only one contact can be established at a given time (i.e., belong to the CP) even if more are feasible through each antenna. A much more complex architecture is shown in Fig. 3c, where two simultaneous contacts are implemented by two cooperative communications subsystems. The latter is the only possible architecture if a non-DTN solution is adopted for the example network, but at the expense of further requirements over the platform power subsystem and weight budget, among others.

In general, CRCs require a selection process. To illustrate the latter, suppose that the example satellite network makes use of the architecture shown in Fig. 3b. In the contact topology of Fig. 1b, a decision must be made for N_2 and N_3 at $k = 2$, 3, and 4 in the FSM model. Indeed, two possible CPs are illustrated in Figs. 4a and 4b. If the first CP is chosen, the network will provide maximum overall contact time, while if the second one is selected, a more fair and connected network is obtained. Both solutions are defined as feasible CPs the network can implement with the specified resources, but they honor different selection criteria: overall throughput or link assignment fairness.

It should be noticed that while being useful for an illustrative example with two feasible solutions, as more nodes, antennas, transponders, or longer topology interval, CRCs are derived in a nontrivial combinatorial problem with exponentially increasing complexity that a network planner must solve before defining the final CP. Furthermore, CPD might be mandated by more complex selection criteria that take into account not only single-hop consideration as in the present example, but also multihop routing path (slashed arrow in Fig. 4), or even the user traffic that is expected to flow on the system.

SELECTION CRITERIA

In general, the problem of CPD lies in selecting from among those contacts that satisfy the communications opportunities represented in the contact topology, and at the same time fulfill TZCs and CRCs. Figure 5 illustrates this group classification. If no constraints exist, the feasible CP solution space expands to that of the contact topology, implying that all combinations are valid for the final network. Also, the original contact topology might reside in the feasible CP space, meaning that it can be directly used for configuring the system without changes. However, the most common scenario requires a selection among the possible CPs, for which a criterion must be defined. The latter is mandatory if network planning automation is required as for large-scale DTN orbiting systems.

In the example topology of previous sections, two initial topology-driven criteria were appointed: maximum contact time and contact assignments fairness. In spite of the fact that these criteria solely depend on topological information, the finest selection can be considered if routing or traffic information is provided. To this end, we provide an overview of different criteria.

Topology-Driven — The topology-driven or single-hop criterion is the simplest and requires only topological information since routing is expected to be dynamically solved in-network. The analysis is solely based on the CP observation, disregarding other system parameters. The most common criteria of this kind are the maximum contact time (MCT) and fair CP (FCP), illustrated in Fig. 4. Models and algorithms are provided in [9] to design the CP with both criteria, proving that MCT delivers CPs with high contact density, but does not necessarily guarantee acceptable network connectivity (as shown in Fig. 4a). On the other hand, FCP prioritizes contacts that are relatively scarce in the topology, providing a fair distribution of them in the final plan. An optimal MILP CPD fairness formulation also exists in [9], authors demonstrate that FCP performs better in routed DTN networks.

Traffic-Driven — A pure traffic-driven criterion is the most controlled scheme and assumes the traffic prediction is fully accurate and can be centrally routed. This implies that the designed contact plan is accompanied by precise and extensive route path information for each traffic data type. Despite this can be challenging, centralized path distribution mechanisms exist such as CGR Extension Block in [11]. With a traffic-driven criterion, the CPD problem can be optimized by means of precise MILP formulations based on the models of [12]. We name this method traffic-driven linear programming (TDLP). On the other hand, a suboptimal yet computationally efficient heuristic mechanism has also been proposed in [4]. This kind of selection criterion provides maximum design optimization and control to the network planner at the expense of flexibility. In other words, if a contact prediction turns out to be inaccurate, or a transponder fails, the traffic-driven selection leaves no place for autonomous network adaptation unless alternative routes are provided.

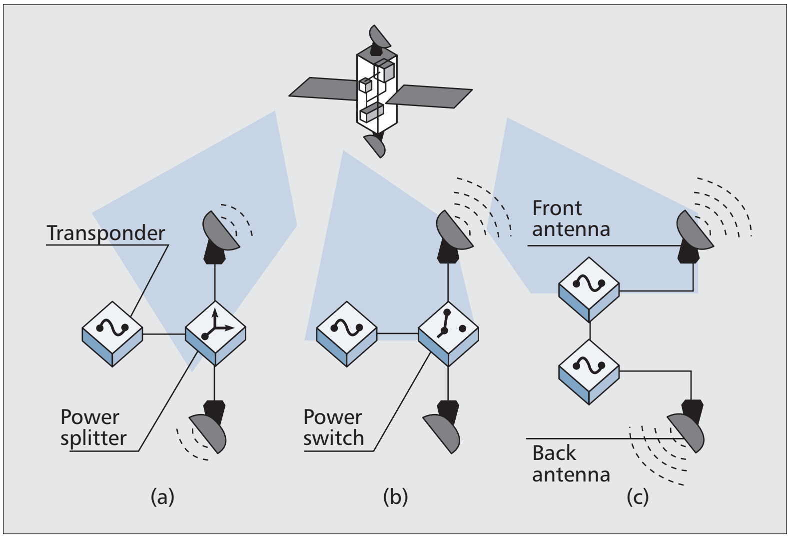

Figure 3. Satellite architecture with a) a power splitter; b) power switch; c) two transponders.

Besides these selection criteria, others could arise depending on the particular purpose of each network. Since several selection methodologies could be required to find out the most appropriate CP, the complexity of such a procedure might be challenging for network operators. Therefore, we envision a CP computation element (CPCE) that can assist or even automate the design of CPs for future spaceborne DTNs. A CPCE shall be capable of determining suitable CPs to support connectivity among nodes and data transfers through the network.

CONTACT PLAN ANALYSIS

In order to evaluate the performance of the existing criteria and solutions described in the previous section, we consider the example topology in the second section. However, we extend the topology interval from the case of half an orbit (illustrated in Fig. 1) up to four orbital periods (spanning a total of 3 h 30 min) in order to better reflect the impact of the CPD mechanisms. Also, in order to allow a higher granularity and accuracy in the design, the topology states K_n longer than 500 s are further partitioned into sub-states. On the other hand, all communications systems are constrained to up to one inter-satellite link per node configured with a 1 Mb/s full-duplex throughput within a 700 km range. The traffic of the scenario is expected to flow equitably from all nodes (N_2, N_3, and N_4) toward N_1, which is expected to deliver the data by means of a space-to-earth high-speed downlink transponder.

In this scenario, we propose to compare topology-driven (FCP) and traffic-driven (TDLP) criteria to illustrate the significance of

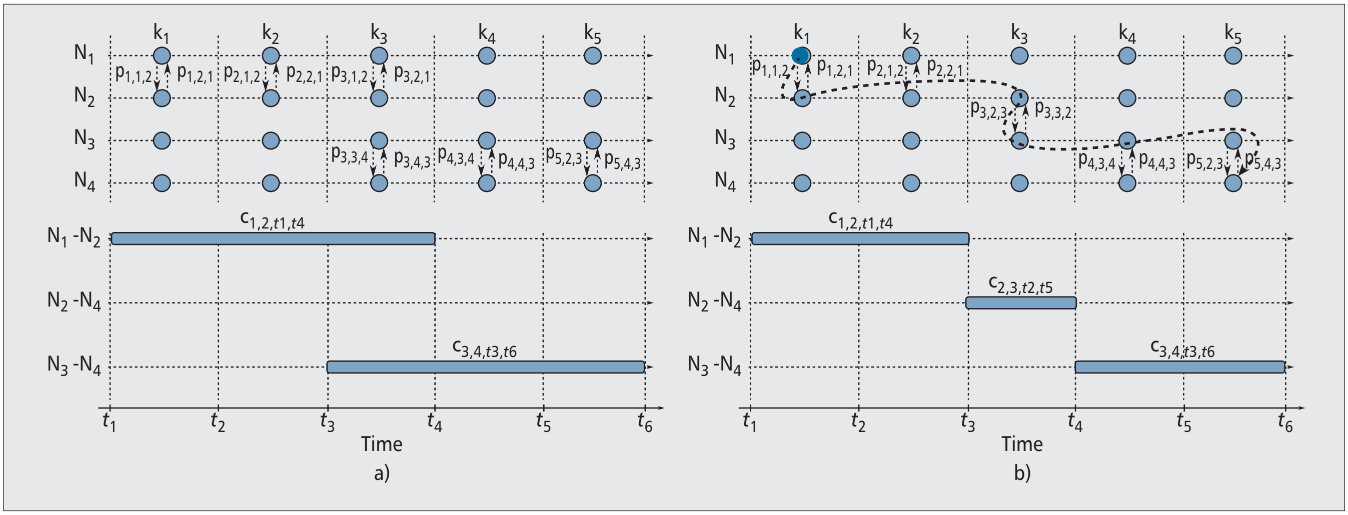

Figure 4. Two possible contact plans: a) maximum throughput; and b) link fairness.

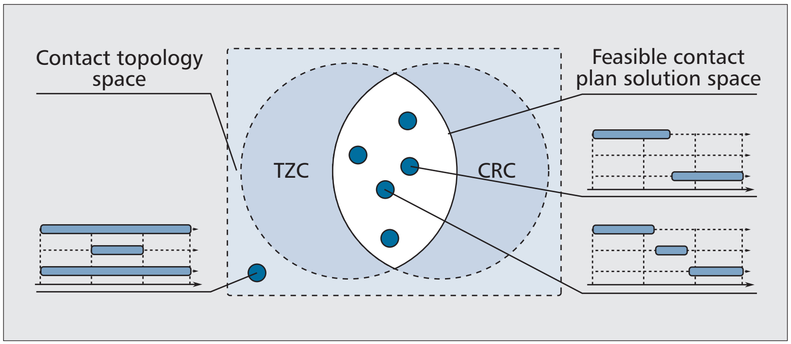

Figure 5. Set of feasible contact plans.

traffic information on the CPD procedures. Besides, we evaluate the physical (PHY) system without any CPD with the aim of illustrating an upper (unconstrained) performance bound. For each of this three methods, we vary the traffic load from $R_o = 1$ (540 Mb/node) to 0.1 (54 Mb/node), where $R_o = 1$ is taken as the traffic that saturates one orbit of the unconstrained CP (PHY). In other words, when enabling all feasible links, the $R_o = 1$ network load can be evacuated to N_1 within a single orbital period. The general hypothesis is that when CPD is necessary (i.e., constraints are considered), the data delivery time will be degraded, especially the measured in FCP as this procedure ignores specific traffic information for contact selection. Besides delivery time, we also evaluate the total contact time as the total accumulated communication time the contact plan uses until all traffic finally reaches N_1.

Results for this scenario are plotted in Fig. 6. It is interesting to note that for $R_o = 1$, the PHY CP can accommodate all traffic within the first orbit period. As the single-interface constraint is taken into consideration by FCP and TDLP, the delivery time (Fig. 6a) increases with different proportions. As expected, TDLP delivers a better CP in terms of delivery time as it takes advantage of the traffic knowledge the CP is expected to serve. Furthermore, since TDLP contacts are chosen as part of a path toward a traffic destination, the CP is more energy-efficient (outperforming PHY), hence minimizing the total contact time. On the other hand, based only on topology parameters, FCP shows an accumulated effect as R_o increases, penalizing the delivery time up to the fourth orbit of the system. Also, the FCP CP indicates several unused contacts that are not considered for routing the traffic to N_1, which, combined with a high delivery time provokes an excessive total contact time metric (Fig. 6b).

CONCLUSIONS

Delay and disruption tolerant networking is emerging as an extension to the current Internet architecture capable of implementing effective networked communications in satellite systems. Among the many benefits, accounting with an autonomous DTN distributed framework can significantly enhance and accelerate the deployment of reliable modern LEO constellations. Furthermore, embracing network disruptions provides an unsought flexibility in traditional Internet-based applications; however, it requires of novel, reliable, and validated mechanisms before being considered for large-scale deployments.

Contact plan design methodologies can be used as a means to optimize limited resources available on satellite networks, and eventually exploit the predictability of these networks. To this end, different modeling techniques, system constraints, selection criteria, and methods were reviewed. We demonstrate that effectively facing the contact plan design can be rewarding but increasingly complex as more information is considered in the planning stage.

Finally, due to the complexity of the design process, we envision the development of CPCEs that can support future operations of future space DTN networks by periodically delivering contact plans that can optimize the performance of these networks. A first commercial-grade CPCE is currently being implemented under the supervision of the authors.

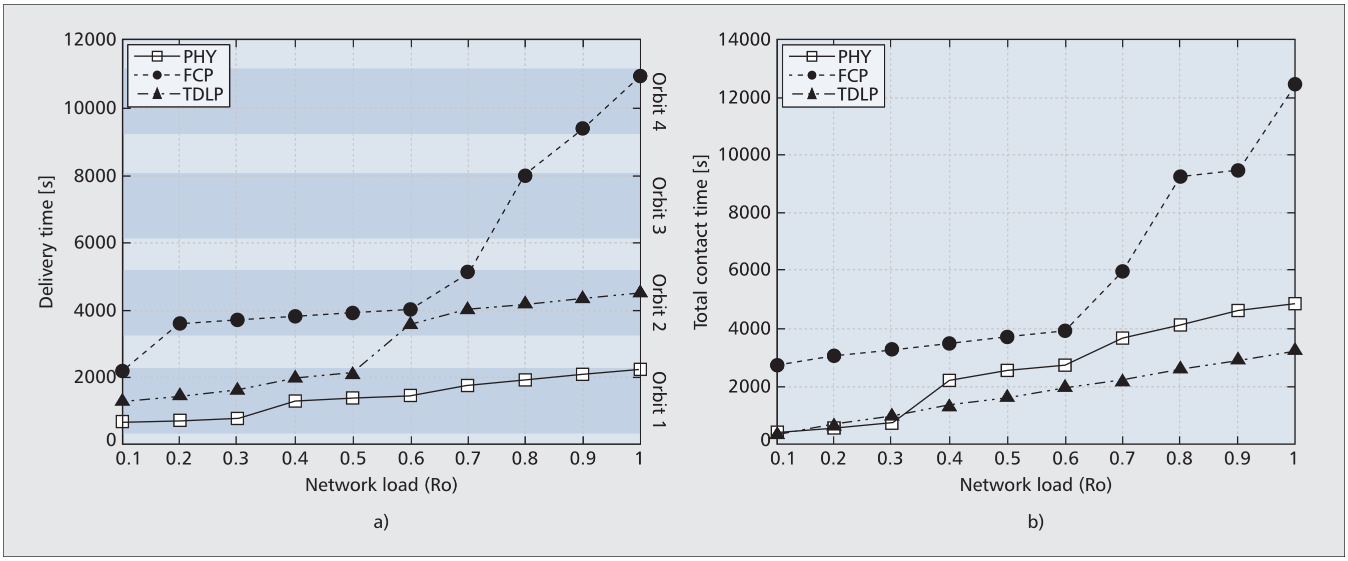

Figure 6. Performance of CPs designed with FCP and MILP model.

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BIOGRAPHIES

JUAN A. FRAIRE received his Telecommunications Engineering degree from the Instituto Universitario Aeronáutico and is completing his Ph.D. in engineering sciences at the National University of Córdoba, Argentina. His research focuses on predictable DTN networking topology design for space-oriented applications. He is a communications protocol architect for STI Company, where he is developing DTN solutions for Earth-observation LEO constellation projects defined in the Argentinian Space Agency (CONAE) National Space Plan.

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