Delay/Disruption Tolerant Network Protocols Applied to Proliferated Satellite Constellations

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Abstract

By increasing connectivity, new opportunities for communication and data routing can be created to overcome the inherent challenges of orbital networks. This paper applies Delay Tolerant Networking (DTN) protocols to large-scale heterogenous networks containing hundreds of spacecraft. Low Earth Orbit (LEO) satellite constellations typically communicate with only their own ground-based infrastructure during intermittent contact opportunities. This restricts the data routing opportunities within the system causing significant delay and disruption challenges. Using inter-satellite links (ISLs) to build on Matryoshka Orbital Networks (MatrON), a computationally efficient model is developed in which LEO satellites and ground stations are modelled as agents traversing nested orbital surfaces or “shells”. The interactions between these agents on different shells are used to generate a contact plan forming a unified network. The DTN routing protocol Contact Graph Routing (CGR) is then implemented to route data through the contact plan of the time-varying network enabling the assessment of viable routes to ensure optimal service delivery. This paper applies CGR to large networks representing a proliferated space architecture and ground targets; analogous to the anticipated orbital environment given current launch trends. The reductions in hop-count and bundle best delivery times provides insight into the potential benefits from large-scale cooperation and indications on the limits for economies of scale in satellite networks.

1. Introduction

Thousands of satellites are launched each year creating an orbital environment that is becoming increasingly congested with a multitude of stakeholders, many of which are deploying large constellations of satellites. According to the United Nations Office for Outer Space Affairs (UNOOSA) annual report on the year 2023, more than 2558 satellites were registered which was the fifth record breaking year in succession with mega-constellations being the driving force behind the growth [1]. Large constellations such as Planet’s constellation of approximately 200 Dove satellites is tasked with imaging all of the Earth each day [2] and Space X’s broadband internet connectivity service Starlink currently consists of over 5000 satellites [3] with aspirations to launch a further 29,988 2nd generation satellites[4], [5]. While Starlink is an anomaly in terms of constellation size, constellations of hundreds of satellites are increasingly common [6] and projections of the orbital environment over the next decade predict upwards of 20,000 new satellite launches [7]. The clear trend is that low Earth orbit (LEO) will be populated with large numbers of satellite constellations operated by different stakeholders that operate independently from one another. With so many satellites in orbit, many opportunities will exist for data transmission between constellations.

Satellite constellations are challenging networks in which communication opportunities are limited [8]. Intermittent contact opportunities with ground station infrastructure are used to transfer data between the spacecraft and ground segment. Between these contact opportunities the satellite must store any collected data until the next contact opportunity. These intermittent contact opportunities restrict the data routing opportunities within the network causing significant delay and disruption challenges. By increasing the number of satellites in the network, new opportunities for communication and data routing are created to overcome these challenges. As LEO becomes ever more densely populated with spacecraft, the orbital environment can be reimagined as a large heterogeneous constellation of constellations. This work integrates them as such to investigate the opportunities for collaboration and cooperation that emerge, which can increase contact opportunities and improve communication for all stakeholders.

Starlink is notable for attempting to increase connectivity by growing the ground segment for users and adding new satellites to the constellation [9]. This method has been a success, bringing reliable internet service to many rural areas previously uncatered for by terrestrial networks[6], [10]. There is therefore evidence to show that being part of a larger network can improve service delivery. However, as previously stated, Starlink’s rapid expansion will have significant impact on the orbital environment. By integrating all satellites in orbit into a single heterogeneous network, the number of new satellites needed for the level of coverage achieved by Starlink would be vastly reduced as resources are shared.

A key aspect of a large orbital network is the ability for satellites to communicate with one another without using a ground station. In [11] Hauri et al investigates the incorporation of Intersatellite links (ISLs), an emerging technology in LEO that enables direct communication between spacecraft in orbit, to satellite constellations. They find that the technology provides several improvements over typical bent-pipe (BP) architecture in the form of network latency, throughput, spectrum efficiency etc. Currently Starlink makes considerable use of ISL technology and other constellations are following suit such as Telesat with their lightspeed constellation [12]. In a scenario in which all satellites could communicate directly using ISL's, each satellite becomes a node of the orbital network, through which data can be routed. Cooperation on this scale would enable a global constellation of constellations through which each stakeholder could transmit data, closing gaps in individual constellation architecture without launching more satellites.

For large scale orbital networks, specialised routing procedures are necessary as Standard Transmission Control Protocol/Internet Protocol (TCP/IP) architectures, which assume a fully connected network, are not well suited to intermittently connected orbital networks [13]. Delay/Disruption Tolerant Networking (DTN) was developed to accommodate the network disruption in such heterogeneous systems. This provides a framework for heterogeneous systems to work together through a series of Convergence Layer Adapters (CLA) which provide the functionality for the DTN Protocol Data Unit (PDU) "bundles" to be carried on each of the different network protocols present in the system [13]. The bundle protocol works by taking a data package, such as an image or sensor reading, and breaking it into several smaller discrete bundles as required. These bundles are routed independently through the network according to each bundle's priority rank. A full description of the bundle protocol and its implementation can be found in [14].

Routing bundles through a time-varying network requires precise knowledge of the available transmission opportunities. Contact Graph Routing (CGR) was introduced by Burleigh [15] and uses a pre-determined contact plan of all transmission opportunities to route data bundles. A contact graph captures the temporal variation in network topology by considering vertices not as network nodes, but as the contact opportunities between them. Each vertex in the graph represents a contact and the edges between them represent the time during which the data must be stored [16]. Contact graphs are created using contact plans which are tables containing information relating to each contact such as satellite ID's, start/end times of contacts and the time it takes for data to travel between satellites; the one-way light time (OWLT).

Since its inception CGR has become the de facto routing framework for space DTN's [16]. Many promising enhancements have been made to improve its performance. In [17] Madoery et al expand CGR to use local traffic information to reduce congestion in the network to great success and in [18] Caini et al analyse a version of CGR called Schedule-Aware Bundle Routing (SABR), finding that it's heuristic-based, best-fit, nature provides significant computational improvements at the cost of optimality. The limitation of these studies is the network size as all networks studied contain small node numbers such as may be found in a small-scale observation or communications constellation; the scalability of the method is unknown. In a congested orbital environment, there could be scope to route data through a large network of hundreds of nodes, increasing routing opportunities and thereby improving delivery times.

To efficiently model such large-scale orbital networks, the authors previously developed an abstraction of the orbital environment called Matryoshka Orbital Networks (MatrON) [19] in which the orbital environment is modelled as a series of nested, rotating shells. Satellites, ground stations and targets are modelled as agents traversing these shell surfaces. This model allows for large numbers of node interactions to be calculated in parallel and the quick production of large contact plans for the entire network. By modelling multiple constellations in this way, a contact plan is produced that collects each constellation into a unified, heterogeneous network.

When the network is modelled, and a contact plan is produced the final step is to use a pathfinding algorithm to find a path through the network. Dijkstra's algorithm assesses every vertex based on the "weight" of the edges between them. In the case of a contact graph this weight is the time between contacts. This ensures that the most optimal route, in terms of time taken, is found [16]. Dijkstra's shortest path algorithm is increasingly resource intensive as the size of the network increases however it is guaranteed to find the shortest path. As bundles will likely have a set Time-to-Live (TTL) beyond which the data is no longer useful, it is crucial that the shortest route is used. It should be noted there are many circumstances in which a contact could be considered unreliable due to out-of-date orbital propagations or on-board software issues. It can therefore be prudent to find multiple viable routes to ensure the data is transferred correctly. Yen's algorithm can be used to find the k shortest routes in a graph [20] and has become a staple in CGR solutions for this reason [16]. This work assumes that all contacts are reliable and will not fail and so routing using Dijkstra's shortest path is sufficient.

This paper applies CGR to networks on a scale of hundreds of heterogenous satellites, representing a proliferated space architecture and ground targets. A contact plan of this network is constructed by adapting the MatrON model to include contacts from ISL connections and routes through this network are found using Dijkstra's algorithm ensuring the shortest paths are taken. The results are then analysed to investigate the potential for cooperation between constellations as well as the scalability of CGR methods.

2. MatrON ISL integration

The MatrON model determines contacts between agents on the rotating shells and ground targets by considering both the earth-centric angle (ECA) between the nodes, and the field of regard (FOR) of the satellite at each timestep. The equations used to capture these are given below and full derivations can be found in [19],

$$\theta_{ECA} = \operatorname{acos}(\cos(\phi_n)\cos(\phi_t)\cos(\lambda_n - \lambda_t) + \sin(\phi_n)\sin(\phi_t)), \tag{1}$$

$$\phi_{FOR} = \operatorname{asin}\left(\frac{z_{FOR}}{R_E}\right) = \operatorname{asin}\left(\frac{x_{int}\sin(\phi_{ss}) + r_{int}\cos(\theta)\cos(\phi_{ss})}{R_E}\right), \tag{2}$$

$$\lambda_{FOR} = \operatorname{atan}\left(\frac{y_{FOR}}{x_{FOR}}\right) = \operatorname{atan}\left(\frac{x_{int}\,\mathrm{s}(\lambda_{ss})\,\mathrm{c}(\phi_{ss}) + r_{int}[\mathrm{s}(\theta)\,\mathrm{c}(\lambda_{ss}) - \mathrm{c}(\theta)\,\mathrm{s}(\lambda_{ss})\,\mathrm{s}(\phi_{ss})]}{x_{int}\,\mathrm{c}(\lambda_{ss})\,\mathrm{c}(\phi_{ss}) - r_{int}[\mathrm{s}(\theta)\,\mathrm{s}(\lambda_{ss}) + \mathrm{c}(\theta)\,\mathrm{c}(\lambda_{ss})\,\mathrm{s}(\phi_{ss})]}\right). \tag{3}$$

Considering the interactions between nodes on the shell surfaces allows for fast and efficient construction of contact plans of large orbital networks. To build contact plans that include cooperation between multiple constellations it is necessary to expand the MatrON model to include Intersatellite links (ISL). These allow the sharing of data between satellites within a defined ISL range. A full contact plan can be built. when all contact opportunities between satellites and ground stations are determined.

Consider that a satellite exists on one shell nested between other shells, above and below. If the ISL range describes a sphere of influence around the satellite, the geometric intersections of this sphere with the other shells, and the shell upon which the satellite travels, describe the contact zones (CZ) of the satellite on each shell within range. Assuming circular orbits, all orbital shells in this scenario are perfect spheres. The intersection can therefore be expressed as follows. Consider the ISL sphere of influence as a perfect sphere centred around the satellite at some point on the x axis, a_1. Consider also an orbital shell centred at the origin of the reference frame with radius a_2. The ISL range, R, is large enough that an intersection occurs.

$$\underline{\text{ISL Sphere on shell 1}} \qquad \underline{\text{Shell 2}}$$
$$(x - a_1)^2 + y^2 + z^2 = R^2 \qquad x^2 + y^2 + z^2 = a_2^2 \tag{4}$$

Where, a_1 and a_2 represent the semi-major axes of the shell upon which the satellite sits & the target shell respectively. R represents the ISL range of the satellite. Setting perpendicular dimensions equal to one another to solve for x,

$$x^2 + R^2 - (x - a_1)^2 = a_2^2, \tag{5}$$

$$x^2 - (x^2 - 2 \cdot x \cdot a_1 + a_1^2) + R^2 = a_2^2, \tag{6}$$

$$2 \cdot x \cdot a_1 = a_1^2 + a_2^2 - R^2, \tag{7}$$

$$x = \frac{a_1^2 + a_2^2 - R^2}{2 \cdot a_1} = x_i, \tag{8}$$

the curve describing the CZ is therefore a planar circle at x_i . The radius of this circle, r_i can be found by using Pythagoras' theorem considering the satellite nadir line as a reference axis,

$$r_i = \sqrt{a_2^2 - x_i^2}, \tag{9}$$

the geometry of this is shown below in Figure 1.

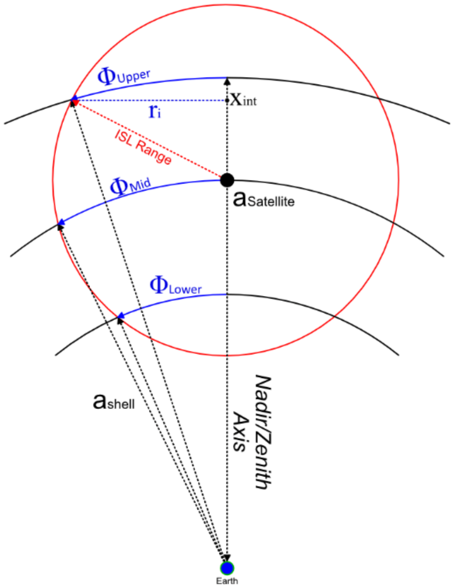

Figure 1: Geometry of ISL sphere with MatrON Shells

The scenario in Figure 1 shows the 3 different CZs, one for each shell in the ISL range. For each CZ the property of most interest is the ECA between the node on the surface and the edge of the CZ. This angle is the Field of Regard (FOR). Every point on the relevant shells with $ECA \leq FOR$ is within contact range of the node. Using Pythagoras theorem, the relationship between ECA, ϕ_{FOR}, and r_i for all shells is evident;

$$\phi_{FOR} = \arcsin\left(\frac{r_i}{a_2}\right), \tag{10}$$

Using Eq. (9) ϕ_{FOR} becomes,

$$\phi_{FOR} = \arcsin\left(\frac{\sqrt{a_2^2 - x_i^2}}{a_2}\right). \tag{11}$$

Using Eq. (8) & Eq.(11) to calculate the FOR between all satellites on all shells expands the MatrON model from [19] allowing for fast construction of contact plans for very large orbital networks. The results in this paper will show the improvements that can be gained by introducing ISL's to satellite constellations.

3. Contact Graph Routing (CGR) Implementation

The CGR algorithm used in this work is taken from work by Lowe et al in 2023 [21] which adapts CGR into an alternative methodology of Contact Graph Scheduling, allowing for task scheduling and data transfer to be combined into one algorithm. The routing section of the algorithm takes a contact plan as an input and builds lists of nodes and contact objects. Data is then routed through the network of contacts according to the plan and the attributes of the nodes, such as OWLT and data transmission rate, using Dijkstra's shortest path and Yens algorithm. The contact plan created by the MatrON model contains node IDs for each node present and contact start/end times. When contacts are extracted for routing, each one is assigned a data transfer rate based on the node attributes. In LEO, distances between satellites are such that OWLT is a small fraction of the contact time. It is therefore considered negligible

Dijkstra's shortest path algorithm functions by traversing every vertex in a graph and assessing the "cost" of traveling to it based upon the connecting edge from the previous vertex. In visiting every possible vertex, the algorithm can assess the lowest cost edges to traverse to reach the destination. In the context of CGR, the vertices represent contact opportunities, and the cost of the edges represents the time between those contact opportunities during which the data is stored onboard the satellite. Figure 2 provides an example of a simple contact graph; each vertex is labelled with the nodes involved in the contact and to the right is the start/end times of the contact. The three coloured lines represent the three viable paths through the graph and their associated best delivery times (BDT) are given.

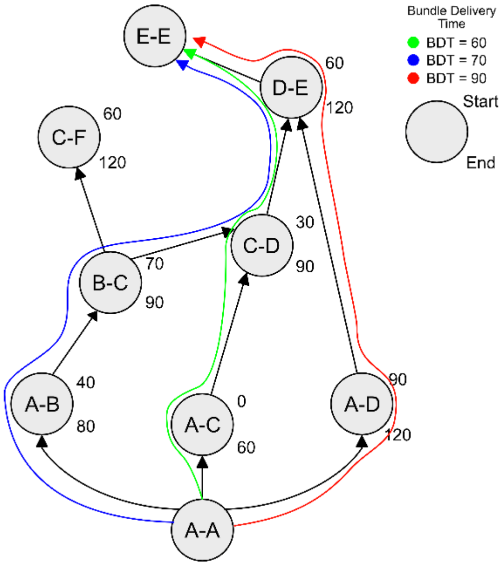

Figure 2: Dijkstra's algorithm on a simple Contact Graph.

4. Model Parameters

All satellites are on circular orbits with randomly generated inclination, right-ascension of the ascending node and altitude. All satellites are also able to establish a link with any other satellite within its ISL range or any ground station within its field of view. Ground stations are placed randomly around the Earth, and it is assumed that every network node has an up-to-date contact plan to be used for routing. The key model parameters common to all results sets are taken from [21] and [19] and can be found in Table 1.

Table 1: Model parameters for test networks

Description	Value	Units
Size of bundle.	100	MB
Data transfer rate.	100	MB/s
Max inter-satellite link range.	1000	km
Field of view of each satellite to ground.	50	degrees

5. Results and Discussion

The following results explore the benefits of adding intersatellite links to a constellation as well as an analysis of using ISLs for inter-constellation cooperation.

5.1 ISL Inclusion

3 random orbital networks, A, B, and C, each containing 5 orbital shells with 20 satellites in each shell and 2 ground stations are initiated. Two bundles are instantiated on a random satellite and target separate ground stations. A contact plan is generated for 24 hours and the bundles are routed through the contact plan to their destination. Figure 3 shows the improvement to BDTs when using ISLs in minutes.

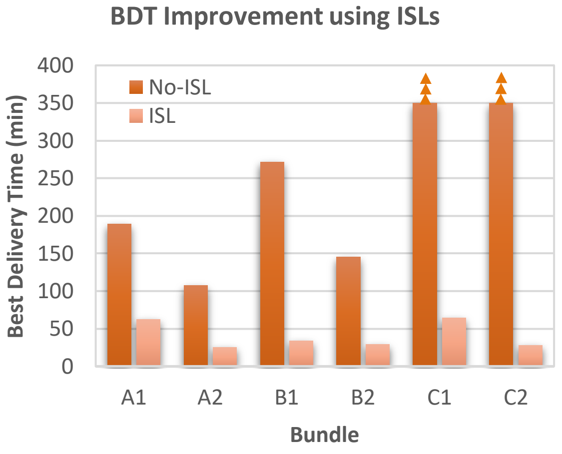

Figure 3: Changes to BDT when introducing ISLs to a network.

The BDT for bundle 1 of network B, B1, reduces from 4.5 hours to approximately 33min. The case of network C is the most dramatic as no viable routes to the targets existed within the 24-hour runtime without the additional connectivity provided by the ISL connections. These results show a clear utility in the implementation of ISL connections and provide strong evidence for the benefits of their use in constellation cooperation.

5.2 Network Cooperation

Figures 4, 5 & 6 show the number of hops per route and BDT for different random network cooperation scenarios. 2 random networks, A&B, are created with the same parameters as the ISL investigation above with the exception that each bundle has a TTL of 2 hours, Both networks are then combined into a new orbital network through which the same data bundles are routed to the same targets but now have access to new contacts. The scenarios tested are for cooperating 30, 120 and 300 node networks.

The most impactful changes can be seen for the 120-node networks. BDT decreases drastically for all bundles except A1. In this case a large change in hop-count contributes to a smaller reduction in BDT. This illustrates the substantial improvements to BDT that are possible with cooperation. These improvements can also be seen in the 30-node networks to a lesser degree due to the comparatively small number of satellites. Bundle A1 uses the additional connections from network B to slightly improve the BDT at the cost of an additional hop. In addition to improved BDT, additional connections enabled the delivery of bundle B1 to its target where initially there was no viable route. This illustrates that being able to use contacts between constellations can allow entirely new opportunities for data bundles to be routed.

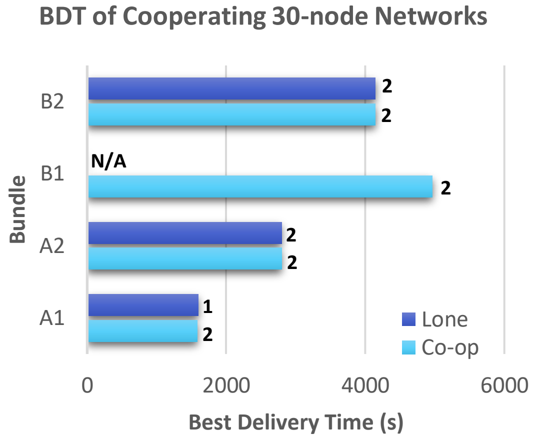

Figure 4: BDT results from two 30-node networks. Hop-count is given alongside each bar.

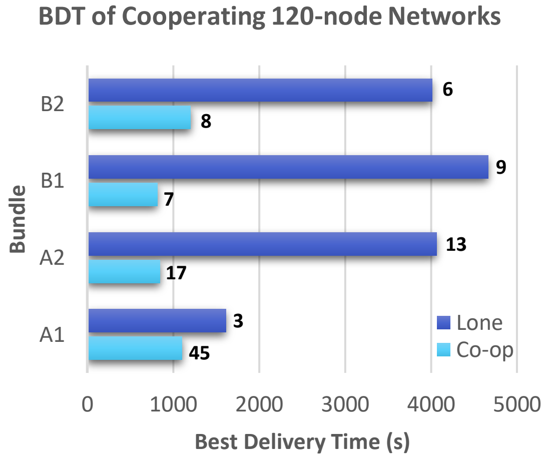

Figure 5: BDT results from two 120-node networks. Hop-count is given alongside each bar.

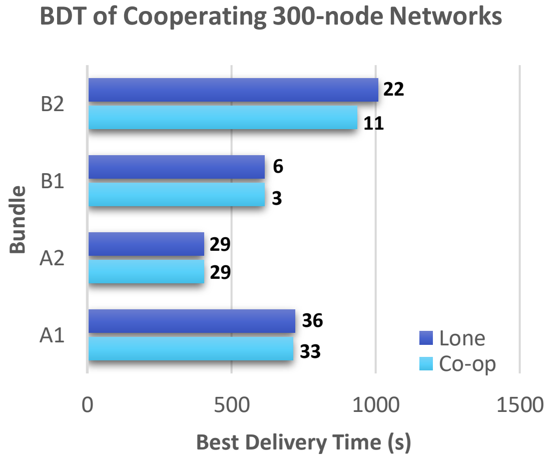

Figure 6: BDT results from two 300-node networks. Hop-count is given alongside each bar.

The 300 node networks are already highly connected compared to the 30 & 120-node networks and so BDT for each bundle is initially low and hop counts are high. When cooperating, hop counts reduce and improvements to BDT are far less substantial than the 120-node case. A decrease in the number of hops is an improvement as it directly results in a reduction of satellite power consumption and reduces congestion in the network. It also increases the overall reliability of the route as there are less chances for transmission failure or otherwise missing contacts. However, a smaller hop-count coupled with diminishing returns on BDT suggests an upper limit to the improvement that can be expected from the cooperation of large constellations in regards to these metrics.

6. Conclusions

This paper has introduced an expansion to the MatrON model and shown the utility in adding ISLs to existing satellite constellations as well as MatrONs utility in building large contact plans for the analysis of proliferated satellite constellations. In that analysis, potential for large scale constellation cooperation was strongly indicated by increased hop-counts and reduced BDT for 120 node networks as well as enabling bundle delivery in 30-node networks where previously there was no viable route. 300-node networks indicated diminishing returns in terms of BTD improvement, however. This suggests the existence of an optimisation challenge in regards to the size of large space DTNs and data delivery.

Acknowledgements

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References

[1] UNOOSA, ‘United Nations Office for Outer Space Affairs 2023 Annual Report - A Year of Transition’, [Online]. Available: https://www.unoosa.org/documents/pdf/annualreport/UNOOSA_Annual_Report_2023.pdf

[2] ‘Planet Monitoring - Satellite Imagery and Monitoring’, Planet. Accessed: Apr. 11, 2024. [Online]. Available: https://www.planet.com/products/monitoring/

[3] E. Howell, T. P. from D. Dobrijevic, and A. M. last updated, ‘Starlink satellites: Facts, tracking and impact on astronomy’, Space.com. Accessed: Apr. 11, 2024. [Online]. Available: https://www.space.com/spacex-starlink-satellites.html

[4] ‘Partial Grant of SpaceX Gen2 Application to Allow E-Band Operations | Federal Communications Commission’. Accessed: Apr. 11, 2024. [Online]. Available: https://www.fcc.gov/document/partial-grant-spacex-gen2-application-allow-e-band-operations

[5] W. Huang, R. Andrada, K. Holman, D. Borja, and K. Ho, ‘A Preliminary Availability Assessment of A LEO Satellite Constellation’, in *2024 Annual Reliability and Maintainability Symposium (RAMS)*, Jan. 2024, pp. 1–6. doi: 10.1109/RAMS51492.2024.10457737.

[6] Y. Shaengchart and T. Kraiwanit, ‘Starlink satellite project impact on the Internet provider service in emerging economies’, *Res. Glob.*, vol. 6, p. 100132, Jun. 2023, doi: 10.1016/j.resglo.2023.100132.

[7] S. Erwin, ‘Industry report: Demand for satellites is rising but not skyrocketing’, SpaceNews. Accessed: Apr. 15, 2024. [Online]. Available: https://spacenews.com/industry-report-demand-for-satellites-is-rising-but-not-skyrocketing/

[8] C. Caini, ‘2 - Delay-tolerant networks (DTNs) for satellite communications’, in *Advances in Delay-Tolerant Networks (DTNs) (Second Edition)*, J. J. P. C. Rodrigues, Ed., in Woodhead Publishing Series in Electronic and Optical Materials. , Woodhead Publishing, 2021, pp. 23–46. doi: 10.1016/B978-0-08-102793-6.00002-3.

[9] ‘Starlink | How Starlink Works’, Starlink. Accessed: Apr. 11, 2024. [Online]. Available: https://www.starlink.com/technology

[10] ‘Starlink’, Starlink. Accessed: Apr. 16, 2024. [Online]. Available: https://www.starlink.com

[11] Y. Hauri, D. Bhattacherjee, M. Grossmann, and A. Singla, ‘“Internet from Space” without Inter-satellite Links’, in *Proceedings of the 19th ACM Workshop on Hot Topics in Networks*, in HotNets ’20. New York, NY, USA: Association for Computing Machinery, Nov. 2020, pp. 205–211. doi: 10.1145/3422604.3425938.

[12] ‘Telesat and SpaceX Announce 14-Launch Agreement for Advanced Telesat Lightspeed LEO Satellites | Telesat’. Accessed: Apr. 30, 2024. [Online]. Available: https://www.telesat.com/press/press-releases/telesat-and-spacex-announce-14-launch-agreement-for-advanced-telesat-lightspeed-leo-satellites/

[13] K. Fall and S. Farrell, ‘DTN: an architectural retrospective’, *IEEE J. Sel. Areas Commun.*, vol. 26, no. 5, pp. 828–836, Jun. 2008, doi: 10.1109/JSAC.2008.080609.

[14] S. Burleigh, K. Fall, and E. J. Birrane, ‘Bundle Protocol Version 7’, Internet Engineering Task Force, Request for Comments RFC 9171, Jan. 2022. doi: 10.17487/RFC9171.

[15] S. Burleigh, ‘Dynamic Routing for Delay-Tolerant Networking in Space Flight Operations’, in

SpaceOps 2008 Conference, Heidelberg, Germany: American Institute of Aeronautics and Astronautics, May 2008. doi: 10.2514/6.2008-3406.

[16] J. A. Fraire, O. De Jonckère, and S. C. Burleigh, ‘Routing in the Space Internet: A contact graph routing tutorial’, *J. Netw. Comput. Appl.*, vol. 174, p. 102884, Jan. 2021, doi: 10.1016/j.jnca.2020.102884.

[17] P. G. Madoery, J. A. Fraire, and J. M. Finochietto, ‘Congestion management techniques for disruption-tolerant satellite networks’, *Int. J. Satell. Commun. Netw.*, vol. 36, no. 2, pp. 165–178, 2018, doi: 10.1002/sat.1210.

[18] C. Caini, G. M. De Cola, and L. Persampieri, ‘Schedule-Aware Bundle Routing: Analysis and enhancements’, *Int. J. Satell. Commun. Netw.*, vol. 39, no. 3, pp. 237–249, 2021, doi: 10.1002/sat.1384.

[19] J. Gribben, R. Clark, C. Lowe, and M. Macdonald, ‘Matryoshka Orbital Networks’, in *74th International Astronautical Congress*, AZE, Oct. 2023. Accessed: Jun. 04, 2024. [Online]. Available: https://strathprints.strath.ac.uk/87732/

[20] J. Y. Yen, ‘Finding the K Shortest Loopless Paths in a Network’, *Manag. Sci.*, vol. 17, no. 11, pp. 712–716, Jul. 1971, doi: 10.1287/mnsc.17.11.712.

[21] C. J. Lowe, R. A. Clark, C. N. McGrath, and M. Macdonald, ‘A delay-tolerant network approach to satellite pickup and delivery scheduling’, *Ad Hoc Netw.*, vol. 151, p. 103289, Dec. 2023, doi: 10.1016/j.adhoc.2023.103289.