Deliverable D3.1:

Inventory of Practice: Topologies and Routing

Deliverable

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1 Executive Summary

This deliverable summarizes the documentation collected regarding the network **topology** shapes and **routing** schemes relevant to MISSION partners. The concrete interest of industrial partners is presented and extended to a broader context with the state-of-the-art contributed by academic partners.

We first present the topologies, which are logical constructs that define the connectivity of space networks. We list traditional **Satellite Constellations** as a case of topologies with continuous connectivity, and **Ring Road Networks** as alternative constellation topologies with discontinuous connectivity. Next, we list routing schemes that are applicable to satellite constellations and ring road networks. The resulting material is expected to serve as an inventory of techniques to implement space networks under the assumption of continuous and discontinuous connectivity.

In particular, we find that INVAP is interested in continuous satellite constellations, while D3TN in the discontinuous ring road network types. GOM has equal interest in both kind of topologies, as long as they are applicable to constrained nano-satellite platforms. From the academic partners, USAAR has recently started research on routing in satellite constellations, while UNC and USAAR have previous works on discontinuous connectivity, especially in routing under uncertain Delay-Tolerant Networks (DTN).

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2 Topologies

Topologies are classified in continuous and discontinuous connectivity. Satellite constellations are the materialization of the former, while ring road networks leverage a discontinuous approach.

Continuous Connectivity. By continuous we understand that there is a dynamic but persistent multi-hop path between the sender and the receiver nodes. In other words, although the nodes on the path change with time, there is always at least one path to connect both sender and receiver (i.e., end-to-end connectivity). The concrete space architecture representing this case are satellite constellations (or mega-constellations), where a multi-hop chain of links is available at all times.

Discontinuous Connectivity. On the other hand, discontinuous topologies are those in which a path between two nodes can be non-existent, and thus disrupted. The path can thus exist only during specific periods of time, and might not be present in other time episodes. This forces intermediate nodes to possibly keep data stored for arbitrary durations until a new link becomes available. In the space use case, these cases are seen when few satellites are available to collect data from a given region, where long connectivity gaps can be present until the next satellite contact is possible. Cases where such a sparse satellite network is used to provide internet connectivity to isolated region are known as ring road networks.

2.1 Continuous Connectivity

Satellite constellations allow for persistent end-to-end paths to exist. These are systems designed to provide Internet type of connectivity using space infrastructures. Different constellation shapes are identified below.

Walker-Star Constellations Early work on satellite constellations was published in 70s by John Walker in [1] and in [2]. The main focus was put on **polar** orbits following a so-called *Walker-Star* configuration on which ascending nodes are distributed over a 180° degree span (two seams are generated between ascending and descending satellites). Walker-Delta constellations can offer coverage of the whole surface of the planet, including the poles (see Fig. 1). Further enhancements known as "streets-of-coverage" were later proposed by Rider [3], Lang [4], and Adams [5].

Walker-Delta Constellations Extensions of the Walker-Star constellation were studied including the work of Ballard [6], which deepened on circular but **inclined** orbits uniformly distributed along the equator (RAAN spread of 360°). These are nowadays known as *Walker-Delta* or Ballard-Rosette constellations. A Walker Delta Constellation has two locally separate overlapping meshes, an ascending and a descending mesh. Walker-Delta constellations concentrate the coverage over populated regions (see Fig. 1).

Other Constellations Most recently, Mortari [7] proposed a new *Flower* constellation type based on elliptical ground-track repeating orbits that was also extended with 2D [8], 3D [9] and 4D lattice [10], as well as necklace [11], and also framed 2D [12] and 3D [13] lattice models. All these studies are geometric analytical approaches, but other heuristics for designing custom constellations have been analyzed in [14].

Shells and Layers Constellations are typically deployed in *shells* at different altitudes in LEO, possibly mixing Walker-Star and Delta types (see Fig. 1). The term *layer* is commonly used to identify different networks spanning LEO, MEO and GEO.

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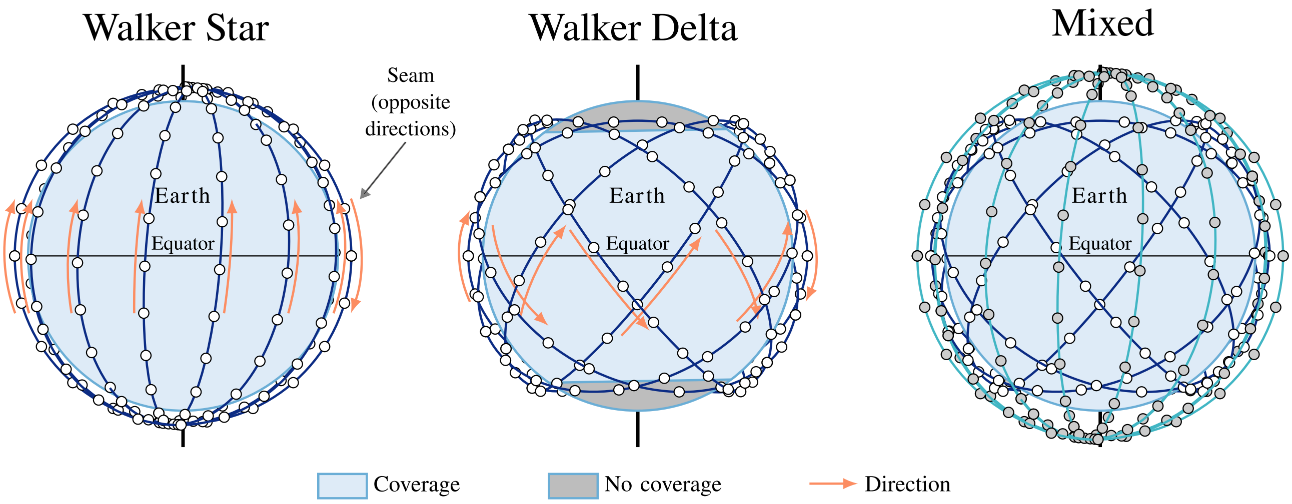

Figure 1: Walker-Star, Walker-Delta, and Mixed topologies [15].

2.1.1 Constellation Projects

Two waves of satellite constellations are listed below. One occurred in the 90s, the other started in 2010 approximately.

First Wave *Globalstar* (24 satellites) deployment started in 1996. An inclined Walker-Delta configuration was leveraged [16]. *Iridium* (66 satellites) followed in 1998 covering higher latitude regions served by polar orbits in a Walker-Star configuration [17, 18]. *Orbcomm* (30 satellites) is another minor constellation offering short burst services [19]. *Teledesic* [20] (initially 924 satellites, then downgraded to 288 [21]) as well as *Celestri* [22, 23] and *Skybridge* were also planned in a Walker-Star formation, but never materialized due to a business crisis in the space sector [24, 25, 26].

Second Wave After 10 year slow-down provoked by such crisis, a new wave of large-scale constellations (a.k.a., mega-constellations) emerged from the private sectors. *O3b* (12 satellites) was deployed in MEO in 2014, and *Starlink* from SpaceX (4425 satellites in 5 shells: 4 Walker-Delta and 1 Walker-Star type) and *OneWeb* (720 satellites, Walker-Star single-shell) are being deployed as of 2022. *Kuiper* [27] (720 satellites in 3 shells) from Amazon, *Telesat* (117 satellites in 2 shells with polar/inclined orbits), among others are on the schedule [28]. Interestingly, neither Kuiper or Starlink exposed the value of the phase shift of the constellation in their FCC filings [29].

2.1.2 Constellation Networks

Satellite network characteristics Spacecraft are characterized by limited on-board processing and storage, highly dynamic topology, high data error rate after transmission, high propagation latency, and uneven traffic pattern along the network. When used in a networked constellation, satellites are typically equipped with four *inter-satellite links* (ISL): two intra-plane (same plane) and two inter-plane (left/right orbital plane).

First Wave Despite *Globalstar* was aimed at providing global voice services, a *bent-pipe* configuration forced the presence of ground station to relay data to [16] (i.e., no inter-satellite linking (ISL) was implemented). *Iridium*, on the other hand, leveraged ISLs to unlock a truly global networked service, no matter the presence of a near by ground site [17, 18]. A similar approach was planned for *Teledesic*, but **Iridium is the only operative satellite constellation from this first wave in the 90s to implement ISLs**. Although the Iridium protocol and routing schemes are closed and proprietary, speculations

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indicates that ATM-like protocols are combined with a centralized and time-variant route table computation (a.k.a., *connection-oriented*, as discussed below) [30]. The short-length of ATM packets imply **processing and transmission delay was a minor effect compared with propagation latency**. Also, the Walker-Star pattern of Iridium **biased early routing research towards this configuration**.

Second Wave Regulatory filings of upcoming mega-constellation including *Starlink*, *Kuiper*, and *Telesat* indicate they will all use high-bandwidth laser ISLs [31]. This means routing will become a more relevant problem, requiring a more general approach in practice. Indeed, mega-constellations are different than Iridium: they feature **inclined orbits** in a **Walker-Star** shape, significantly **larger satellite fleets**, and **multiple layers** in some cases. Also, **larger packets** (e.g., Ethernet-like Jumbo frames) are expected over a significantly **larger amount of hops**, so processing time and thus **hop count becomes more important** than for the Iridium case. A particular property of Walker-Delta is that **users can be covered simultaneously by both ascending and descending satellites**, which can lead to completely different routes toward the destination [32] (an ascending satellite only connects to other ascending satellites, and likewise a descending satellite [33]). This adds to the satellite selection problem in multiple-shell constellations. Thus, the challenges towards routing in future mega-constellations are:

1. Most generic connection-oriented schemes (centralized route computation) will likely not scale sufficiently to mega-constellations.
2. Most performant but specific connection-less (distributed route computation using Walker-Star specific rules) will need to be revised/adapted.
3. Phase shift considerations will need to be studied in varying inclinations adopted by Walker-Delta constellations.
4. Satellite selection between ascending/descending orbits and multiple shells at sight will need to be developed.

USAAR Recent work by this partner is based on the Walker-Delta pattern, with varying inclinations and phase shift considerations. They develop a model based on hop count theory for Walker-Delta mega-constellations proposed by Chen et al. [34]. Previous work has focused on adaptive routing for Walker-Delta [35]. Also, the structural properties of Walker-Delta have been studied in [36]. USAAR research is adapting this research line for future mega-constellations.

2.2 Discontinuous Connectivity

Topologies with discontinuous connectivity differ from the current digital connectivity expansion based on the goal of universal continuous connectivity. The implications of commitment to this model might not be evident unless we move beyond the frontier of terrestrial communication, into cis-lunar space and beyond. Due to the light propagation speed limit and planetary occlusion, continuous connectivity as sought for by mega-constellations will become impractical or impossible in such conditions, even with the best possible technologies.

The core construct derived from this vision is framed in the “ring road network” (RRN) concept, which was first presented in 2011 [37] and recently revamped by D3TN in [38]. The remainder of this section presents and discusses content from this last paper from this MISSION partner. Note that D3TN is the leader of WP3.

2.2.1 Ring Road Networks

In an RRN, overflying low-Earth orbit (LEO) satellites act as data mules to receive, **carry**, and deliver data from and to places that lack Internet connectivity. The main advantage of this concept is that it can

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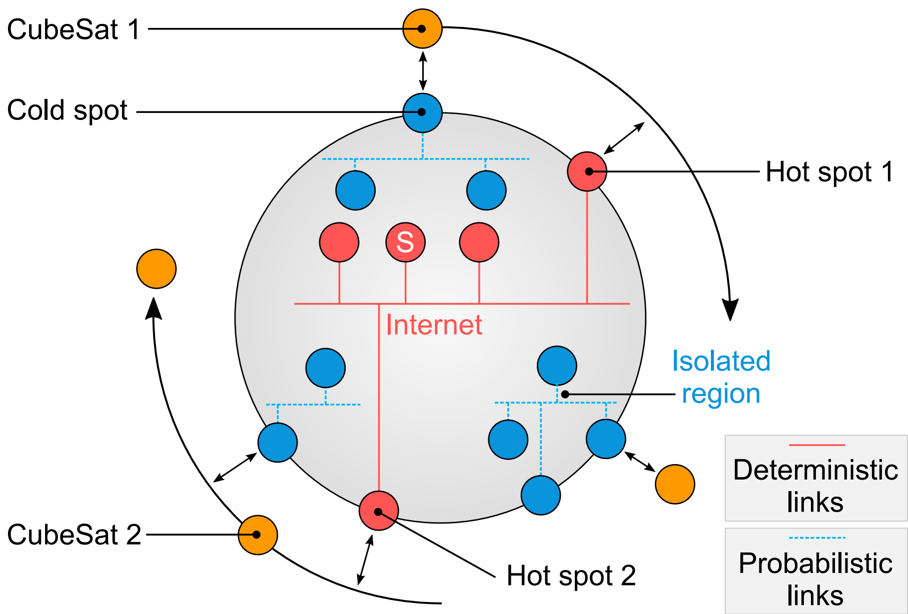

Figure 2: RRN diagram. Nodes connected to the isolated *cold spot* can relay bundles to *cubesat 1*, which carries the data until flying over *hot spot 1*. The bundle can then reach the server on the Internet (S), which determines that the optimal return path is via *hot spot 2* and *cubesat 2*. Image taken from [38].

be implemented with Delay-Tolerant Networking (DTN) protocols and inexpensive nano-satellites such as CubeSats. Because of its delay-tolerant nature, even a single nano-satellite can provide (extremely) high-latency connectivity services on a global scale. The addition of more satellites will enable the reduction of the end-to-end delay and the increase of the overall system capacity. An operative RRN will thus allow currently disconnected users to run Wikipedia searches, receive remote medical assistance, participate in global market stores, among many other services we are used to in urban environments. The only difference is that replies and feedback might arrive minutes or hours after queries are issued.

Ring Road Networks are composed of low-cost, LEO satellites. Due to the limited deployment and operational costs, they are perfectly suitable for providing Internet access to disadvantaged populations while possibly also relaying data inexpensively for other classes of users. As data in an RRN is transported by the LEO satellites using DTN protocols in a store-carry-and-forward manner, high end-to-end communication delays are given (see [37] for details). Building upon the initial idea of combining small satellites and DTN presented in 2008 [39], the technological and scientific landscape in this context has shown major advances that favor the deployment of RRNs before the end of this decade [37, 40, 41, 42, 43]. In contrast to existing satellite missions which aim to support the conversational, synchronous exchange of data, RRNs aim to provide reliable epistolary data transfer. They enable asynchronous connectivity to otherwise isolated network nodes on Earth (called "cold spots" in RRN terminology).

As RRNs can be built incrementally starting with a single satellite (e.g., in contrast to mega-constellations such as Starlink based on thousands of ≈250 kg satellites) and as they do not require continuous connectivity among satellites, deployment costs are very low (see [37] for details). By tolerating episodic contacts, RRNs may comprise solely nadir-pointing CubeSats in LEO: each satellite retains in-transit data collected from cold spots in a queue in its own local storage medium, awaiting its "hot spot" overflights. In RRN terminology, hot spots are ground stations that have Internet access, by which data can be forwarded to and answered by an application server (see Fig. 2).

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2.2.2 Related Research

This section summarizes the most relevant research in the context of RRNs.

Taxonomy and Tools A comprehensive taxonomy of RRNs has been presented in [41]. In this research, an investigation of the delay and path length characteristics is discussed. The authors evaluate RRN fleets from 10 to 50 satellites. Inter-satellite linking (ISL) was evaluated for RRNs in [40]. Results show that the delivery ratio could be improved up to 10% in Walker formations comprised of 12 satellites, even though congestion issues were identified. A vast number of different simulation tools have been used and developed to analyze algorithms in RRN, e.g., the ONE, *ns-3* [44, 45], *DtnSim* based on *Omnet++* [40], *aiodtnsim* [43], and further custom toolchains (e.g., [42]).

Contact Prediction The estimation of the characteristics of transmission opportunities in RRNs was discussed and analyzed in concert with an extended deterministic routing scheme based on several earlier publications in [43]. For the validation, multiple RRN scenarios with 6-9 satellites and 10-15 ground stations have been derived from data sets collected via a global ground station network.

D3TN As discussed in their blog post[1], D3TN has performed a series of in-orbit testing of the RRN paradigm with support from ESA's OPS-SAT nano-satellite.

D3TN firstly performed a "ping-pong" message exchange between a single terrestrial µD3TN instance (D3TN DTN protocol implementation) and the one running on the OPS-SAT. After verifying that the basic scenario went smooth, more and more complexity was introduced to cover more realistic use cases.

In the second test, D3TN added their Ground Station Dispatcher component to the setup, which allowed to multiplex access to ESA's SMILE ground station. This way, many ground stations were emulated even though only one was accessible. This is particularly useful to test "Ring Road" scenarios, where a decoupled site without internet access (cold spot) communicates with a site with internet access (hot spot) via a periodically passing satellite.

3 Routing

In this section we aim at making a brief survey of the existing routing schemes for continuous connectivity and discontinuous connectivity topologies.

3.1 Continuous Connectivity

Existing surveys about LEO satellite network routing are either old and not broad enough [46] (link), or just bad [47] (link). No survey is available for mega-constellations. Thus, in this deliverable, we provide an inventory of practice based on recent research conducted by USAAR.

Network model This survey classifies routing in two types: (*i*) virtual (grid) topology (or *time splitting*). Discrete time slices or snapshots are used, and no dynamic behavior (QoS, failures) can be captured, (*ii*) virtual node (or *region splitting*). Fixed locations are defined and the closest satellite in the constellation is assigned a temporary logical address and the corresponding routing table. It can be used with Walker-Star only [48].

3.1.1 Single-Layer/Shell Routing Schemes

Below, we list existing solutions for single-layer/shell routing schemes.

[1] https://d3tn.com/blog/posts/2021-05-25-more-opssat-tests/

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Discrete-Time Dynamic Virtual Topology Routing (DT-DVTR) (1997) [30] Routing for periodically variant (cyclic) ISL networks (with orbit control). Works off-line (planning phase) and splits the topology in discrete slices (space-time graph). In each slice, shortest paths are computed using Dijkstra's algorithm, and final path selection is performed guided by minimization of in-orbit handovers/jitter. Routes are fixed after planning.

- Network model: virtual topology
- Path computation model: connection-oriented (full path is computed)
- Optimization metrics: minimal hand-over jitter (operational constraint)
- Optimization method: Dijkstra's algorithm

Finite State Automata (FSA) (1998) [49] Divides the topology in discrete states corresponding to an equal-length interval assuming a periodic/cyclic system. Combines the routing with the link assignment problem. Leverages an MILP model, solved with iterative heuristics (e.g., simulated annealing). The optimization metric is to maximize the minimum residual capacity (fairness). Routes are fixed after planning.

- Network model: virtual topology
- Path computation model: connection-oriented (full path is computed)
- Optimization metrics: minimum residual capacity (fairness)
- Optimization method: MILP and Simulated Annealing

Compact Explicit Multi-path Routing (CEMR) (2005) [50] Also divides the topology into discrete states. But introduces a labeling and encoding for ISL hops along a path (loop-free). It considers queuing and propagation delay as the optimization metric, and allows for multi-path load balancing forwarding. Routes are fixed after planning.

- Network model: virtual topology
- Path computation model: connection-oriented (full path is computed)
- Optimization metrics: queuing and propagation delay
- Optimization method: any K-shortest path algorithm

Explicit Load Balancing (ELB) (2006) [51] Aims at minimizing the load on congested satellites by exchanging congestion status in-orbit *(soon to be congested* message broadcasted). Uses queue ratio and reduction ratio as metrics to reduce packet drop. Adapts pre-computed routes dynamically.

- Network model: virtual topology
- Path computation model: connection-oriented (full path is computed)
- Optimization metrics: queue ratio and reduction ratio
- Optimization method: Dijkstra's Shortest Path

Cross-layer design Ant-colony optimization-based Load-balancing routing algorithm (CAL-LSN) (2014) [52] (link) Uses the physical layer information to make routing decisions based on a multi-objective optimization model considering smallest bandwidth limit, the upper limit of the LEO satellite network delay tolerance, and link disruption probability. Adapts pre-computed routes dynamically.

- Network model: virtual topology
- Path computation model: connection-oriented (full path is computed)
- Optimization metrics: physical layer bandwith
- Optimization method: Ant Colony Optimization

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Priority-based Adaptive Routing (PAR/ePAR) (2007) [53] Utilizes the historical information and ISL buffering status to make the decision at each node along the path. Uses virtual topology model. Routes are computed on the fly, hop-by-hop. Uses minimum hop count as a metric to reach the destination, and aims at a uniform traffic distribution.

- Network model: virtual topology
- Path computation model: connection-less (path is constructed hop-by-hop)
- Optimization metrics: minimum hop count
- Optimization method: Direction estimation algorithm

Dynamic Detection Routing Algorithm (DDRA) (2014) [54] Uses virtual topology model. Shortest path algorithm is used to compute the initial routes. Acknowledgment messages and link status are tracked so that routing reacts to latest status.

- Network model: virtual topology
- Path computation model: connection-less (path is constructed hop-by-hop)
- Optimization metrics: Queue congestion
- Optimization method: Shortest path algorithm

Location-Assisted On-Demand routing (LAOR) (2007) [55] Proposed for IP-based LEO satellite systems. On-demand route request and route reply (high overhead of route discovery flooding). Does not consider the node or link failures.

- Network model: virtual node
- Path computation model: connection-less (path is constructed hop-by-hop)
- Optimization metrics: propagation delay or the sum of the propagation and queuing delay
- Optimization method: request-reply, shortest path

Destruction-resistant on-Demand Routing (DODR) (2007) [56] LAOR + Does consider the node or link failures. It shrink the flooding area by using a priori direction information.

- Network model: virtual node
- Path computation model: connection-less (path is constructed hop-by-hop)
- Optimization metrics: propagation delay or the sum of the propagation and queuing delay
- Optimization method: request-reply, shortest path

Datagram Routing Algorithm (DRA) (2000) [57], (2001) [58] Decisions are made locally at a node for each packet without using Dijkstra algorithm. Model based in static grid of logical locations above the Earth. Higher priority to transmit data through ISLs at high latitudes, but results in load imbalance. Routing overhead is zero due to the absence of control messages for collecting topology information.

- Constellation model: Walker-star, no phase shift
- Network model: virtual node
- Path computation model: connection-less (path is constructed hop-by-hop)
- Optimization metrics: Hop count
- Optimization method: Dijkstra algorithm

Low-Complexity Routing Algorithm (LCRA) (2015) [59], and Low-Complexity Probabilistic Routing (LCPR) (2015) [60] Both proposed for polar orbit constellations. Same logical position information than DRA. LCRA improves the DRA load imbalance by considering propagation delay and queuing delay as well as balancing the traffic load to avoid congestion. LCPR allows uses the congestion status information collected from its neighbors. LCPR can reduce the computational and storage complexity on board when compared to the DV-DVTR and FSA protocols.

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- Constellation model: Walker-star, no phase shift
- Network model: virtual node
- Path computation model: connection-less (path is constructed hop-by-hop)
- Optimization metrics: Queue delay
- Optimization method: Leverages buffer announces from first-hop neighbors to avoid congestion

Localized Routing Scheme (LRS) (2003) [61] Model based on a mesh-like Manhattan Street Network (MSN). Reduces the size of routing tables calculated onboard by means of hierarchical routing. Two routing techniques that are divided into intra-zone routing and inter-zone routing. A coordinating node is elected within each zone. No load balancing in the inter-zone routing.

- Constellation model: Walker-star (seam), no phase shift, MSN, Iridium use case.
- Network model: virtual node, binary addressing
- Path computation model: connection-oriented
- Optimization metrics: shortest hop
- Optimization method: Dikjstra's algorithm and direction determination

Satellite network Link State Routing (SLSR) (2014) [48] Same MSN model than LRS. This paper states that “the virtual node approach is only applicable to polar orbit constellations". Routing happens in two phases: 1) routing tables calculated off-line (propagation delay), 2) topology updates based on failures or congestion (flooding).

- Constellation model: Walker-star, no phase shift, MSN
- Network model: virtual node - MSN
- Path computation model: connection-less
- Optimization metrics: link propagation delay and link queuing delay
- Optimization method: Dijkstra shortest path algorithm

Software Defined Routing Algorithm (SDRA) (2017) [62] Satellites act as switches, which are only responsible for forwarding data according to the flow table and inform the controllers of the network status. If no flow table is present, it is requested to the controller on-demand. The source node determines both the next hop and the hop after the next. It attaches the hop after the next in the packet header, so the next hop does not need to conduct path calculation. This process continues until the packet reaches the destination.

- Constellation model: Walker-star, no phase shift
- Network model: SDN (a master controller + several slave controllers)
- Path computation model: connection-less (path computed hop by hop -two hops-)
- Optimization metrics: queueing delay
- Optimization method: custom direction based algorithm

Other schemes are listed below, but not classified (on-going work):

Disruption Tolerant Distributed Routing (DTDR) (2022) [63]

Roth Geographical Routing Scheme (ROTH) (2020) [64] (link)

Longer Side Priority (LSP) Routing (2019) [65] (link)

Routing Based on Minimal-Connected-Component (MCC) (2012) [66]

Distributed Hierarchical Routing Protocol for Non-GEO (DHRP) (2004) [67]

Adaptive routing for packet-oriented ISL networks (2002) [68]

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Traffic-Class Dependant and Oscillation supression (2004) [69] (2007) [70] Regarding multiple-layer/shell schemes, we plan to extend the survey into these configurations. However, as discussed with the partners in the workshop at INVAP, it is not yet fully clear how connectivity will be established between layers/shells yet. Thus, routing techniques can't yet be defined. We plan to deepen into this discussion further in the following months.

3.2 Discontinuous Connectivity

Routing in discontinuous connectivity falls into the Delay-Tolerant Networking (DTN) routing family, where connectivity is rather captured by contacts instead of time-evolving links. When applied to satellite or space networks, Contact Graph Routing (CGR) is the mainstream solution. CGR profits from a contact plan comprising the future connectivity of the space network. Indeed, predictable trajectories of spacecraft in orbit (or in interplanetary trajectory) can be pre-computed including the visibility among nodes. CGR has been surveyed by UNC members in [71]. Content from this paper is presented below.

3.2.1 Contact Graph Routing

In DTN it is not possible to use traditional routing schemes based on stable connections. In particular, it is not enough to simply determine the next hop (next neighbor to send the traffic to) from an analysis of current network topology; it is necessary to decide *when* to send data depending on *when* it is expected to arrive via delayed and disrupted links. The consideration of the time dimension is an aspect that challenges any underlying routing algorithm. Fortunately, in space networks it is possible to know the future connectivity of the assets [72], which may be expressed in a *contact plan* defining the expected resources that the space network will have for transporting data. These conditions inspired the creation of new graph models, time-evolving abstractions, and algorithm adaptations of the Contact Graph Routing (CGR) framework. CGR is unique in the sense that it is the sole approach (of which the authors are aware) that integrates the set of techniques capable of coping with these challenges from a practical perspective. CGR is the most mature autonomous routing fabric for the forthcoming Space Internet. But CGR is complex. Its dynamics deserve particular attention and care.

Routing and Forwarding The contact plan serves as input for the routing routine with CGR sitting at its core. Algorithmic approaches for CGR are leveraged to compute the paths to destinations in the network. The resulting routes not only identify which next hop node to forward the bundle (DTN data units) to but also indicate the best delivery time (BDT), the route volume limit ($volume$), and the interval on which this route is valid for transmission (tx_win). Among others, these metrics are computed by CGR and stored in route tables. In the case that routes are computed in a centralized node, the resulting tables must be distributed to DTN nodes in timely fashion. Finally, the forwarding process is responsible for selecting the best route, out of many on the route table. This selection considers local conditions that are only available at that forwarding moment such as local time, the size and priority of the data to be forwarded, and current queue backlog conditions. The best route is thus expected to provide adequate resources for successful delivery of the bundle. Based on the selected route, the bundle is placed in the outbound queue to the node that is identified as the next hop on the route. Once in the queue, the bundle might be transmitted immediately or kept in storage until the next contact occurs.

Chronology CGR was first mentioned as an interplanetary routing approach by Scott Burleigh in 2008 [73]. IETF drafts were also proposed for CGR in 2009 [74] and 2010 [75]. By then, CGR was being periodically released with ION [76]. The first improvements came in 2011 with the proposal of source routing extensions by Edward Birrane in [77, 78], documented in an IETF draft [79]. In

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that same year, the adaptation of Dijkstra in CGR was introduced by Segui *et al.* in [80]. By profiting from a monotonically increasing time-related cost function, this contribution provided CGR with a solid algorithmic framework. In 2012, Birrane et al. presented an extended vision of CGR including prevention of routing loops and multiple destination analysis [81]. At the same time, Carlo Caini *et al.* argued in favor of implementing CGR as a routing solution for near-Earth Low-Earth Orbit (LEO) satellite networks [82, 83, 84]. Similar studies followed afterwards [85, 86, 87], especially in the context of “ring-road" networking, an inexpensive data mule approach for relaying data to and from isolated networks [88, 89, 90, 91]. In 2014, Bezirgiannidis *et al.* made the first steps in modeling the impact of traffic in bundle delivery time estimation together with overbooking management techniques [92, 93]. At about the same time, Fraire *et al.* explored congestion mitigation by proper volume annotations in CGR routes combined with source routing updates [94, 95]. Araniti *et al.* summarized the advances and experimental experiences with CGR up to 2015 in [96], the most cited CGR article at the time of this writing. In 2016, Burleigh *et al.* proposed an opportunistic enhancement to CGR so that unplanned contacts could be correctly reacted upon and included in the routing decisions [97]. Ruhai Wang *et al.* then presented the first investigations into CGR scalability [98], which motivated later contributions by Madoery *et al.* via efficient forwarding [99] and region-based approaches [100, 101]. Initial CGR reliability studies followed in 2017. Juan Fraire *et al.* showed how CGR behaved under uncertain contact plans [102, 103], for which reliable CGR variations based on state-of-the-art computer science models were introduced [104, 105, 106]. Scalability as well as uncertain and opportunistic CGR extensions are among the most active and promising research lines in CGR. In 2018, route table management strategies were also analyzed by Fraire *et al.* in [107]. It was from this contribution that Yen’s algorithm became the default routing management approach for CGR in ION. In 2019, a spanning-tree formulation was proposed as a CGR alternative to compute routes to several destinations [108], and a partial queue information sharing was introduced in [109]. In that same year, the Schedule Aware Bundle Routing (SABR) recommended standard (blue book) was released by CCSDS recommending CGR as the routing procedure for the Solar System Internet [110]. As the development of this extensive ecosystem demonstrates, CGR has become something more than a simple algorithm. CGR is a comprehensive process for tackling the operation and management of a scheduled space DTN. As such, it is quite unique when compared with other routing approaches.

Algorithm CGR is based on a combination of Dijkstra and Yen’s algorithms, which explanation is out of scope of the current deliverable. The interested reader is refereed to [71] for an in-detail presentation of the route determination process.

Routing in RRN A routing trade-off regarding the amount of available topological knowledge coined *spot of maximum knowledge* has been evaluated in a simulated Lunar network comprising 6 satellites in Lunar orbit supported by NASA’s Deep Space Network (DSN) ground stations [42]. A Selection scheme for routing via specific hot spots was presented in [44] and further energy-aware routing schemes for RRN scenarios were explored in [45].

References

[1] J. G. Walker, “Circular orbit patterns providing continuous whole Earth coverage,” ROYAL AIRCRAFT ESTABLISHMENT FARNBOROUGH (UNITED KINGDOM), Tech. Rep., 1970.

[2] J. Walker, “Continuous whole-Earth by circular-orbit satellite patterns,” *Aircr. Establ*, vol. 78, p. 11169, 1977.

[3] L. Rider, “Analytic design of satellite constellations for zonal Earth coverage using inclined circular orbits,” *Journal of the Astronautical Sciences*, vol. 34, pp. 31–64, 1986.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101008233.

[4] T. J. Lang, “Symmetric circular orbit satellite constellations for continuous global coverage,” *Astrodynamics 1987*, pp. 1111–1132, 1988.

[5] T. J. Lang and W. S. Adams, “A comparison of satellite constellations for continuous global coverage,” in *Mission design & implementation of satellite constellations*. Springer, 1998, pp. 51–62.

[6] A. H. Ballard, “Rosette constellations of Earth satellites,” *IEEE transactions on aerospace and electronic systems*, no. 5, pp. 656–673, 1980.

[7] D. Mortari, M. P. Wilkins, and C. Bruccoleri, “The flower constellations,” *The Journal of the Astronautical Sciences*, vol. 52, no. 1, pp. 107–127, 2004.

[8] M. E. Avendaño, J. J. Davis, and D. Mortari, “The 2-D lattice theory of flower constellations,” *Celestial Mechanics and Dynamical Astronomy*, vol. 116, no. 4, pp. 325–337, 2013.

[9] J. J. Davis, M. E. Avendaño, and D. Mortari, “The 3-D lattice theory of flower constellations,” *Celestial Mechanics and Dynamical Astronomy*, vol. 116, no. 4, pp. 339–356, 2013.

[10] D. Arnas, D. Casanova, and E. Tresaco, “4D lattice flower constellations,” *Advances in Space Research*, vol. 67, no. 11, pp. 3683–3695, 2021.

[11] D. Casanova, M. Avendano, and D. Mortari, “Necklace theory on flower constellations,” *Spaceflight Mechanics*, vol. 140, 2011.

[12] D. Arnas, D. Casanova, and E. Tresaco, “2D necklace flower constellations,” *Acta Astronautica*, vol. 142, pp. 18–28, 2018.

[13] D. Arnas, D. Casanova, E. Tresaco, and D. Mortari, “3-Dimensional necklace flower constellations,” *Celestial Mechanics and Dynamical Astronomy*, vol. 129, no. 4, pp. 433–448, 2017.

[14] L. Jia, Y. Zhang, J. Yu, and X. Wang, “Design of mega-constellations for global uniform coverage with inter-satellite links,” *Aerospace*, vol. 9, no. 5, p. 234, 2022.

[15] I. Leyva-Mayorga, B. Soret, B. Matthiesen, M. Röper, D. Wübben, A. Dekorsy, and P. Popovski, “NGSO constellation design for global connectivity,” *arXiv preprint arXiv:2203.16597*, 2022.

[16] R. WIEDEMAN, A. SALMASI, and D. Rouffet, “Globalstar-mobile communications where ever you are,” in *14th International Communication Satellite Systems Conference and Exhibit*, 1992, p. 1912.

[17] R. J. Leopold, “The iridium communications systems,” in *[Proceedings] Singapore ICCS/ISITA92*. IEEE, 1992, pp. 451–455.

[18] ——, “Low-Earth orbit global cellular communications network,” in *ICC 91 International Conference on Communications Conference Record*. IEEE, 1991, pp. 1108–1111.

[19] J. J. Morales, J. Khalife, A. A. Abdallah, C. T. Ardito, and Z. M. Kassas, “Inertial navigation system aiding with orbcomm LEO satellite doppler measurements,” in *Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018)*, 2018, pp. 2718–2725.

[20] M. A. Sturza, “The Teledesic satellite system,” in *Proceedings of IEEE National Telesystems Conference-NTC'94*. IEEE, 1994, pp. 123–126.

[21] D. P. Patterson, “Teledesic: a global broadband network,” in *1998 IEEE Aerospace Conference Proceedings (Cat. No. 98TH8339)*, vol. 4. IEEE, 1998, pp. 547–552.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101008233.

[22] G. B. Shaw, "The generalized information network analysis methodology for distributed satellite systems," Ph.D. dissertation, Massachusetts Institute of Technology, 1999.

[23] R. J. Leopold, "CELESTRI/sup TM/Ka-Band sharing," in *1998 IEEE Aerospace Conference Proceedings (Cat. No. 98TH8339)*, vol. 4. IEEE, 1998, pp. 553–560.

[24] C. Christensen and S. Beard, "Iridium: failures & successes," *Acta Astronautica*, vol. 48, no. 5-12, pp. 817–825, 2001.

[25] E. W. Ashford, "Non-GEO systems—where have all the satellites gone?" *Acta Astronautica*, vol. 55, no. 3-9, pp. 649–657, 2004.

[26] M. Sweeting, "Modern small satellites-changing the economics of space," *Proceedings of the IEEE*, vol. 106, no. 3, pp. 343–361, 2018.

[27] C. Henry, "Amazon's Kuiper constellation gets FCC approval," *Space News*, 2020, Accessed on: Sep. 11, 2020. [Online]. Available: https://spacenews.com/amazons-kuiper-constellation-gets-fcc-approval

[28] I. Del Portillo, B. G. Cameron, and E. F. Crawley, "A technical comparison of three low Earth orbit satellite constellation systems to provide global broadband," *Acta astronautica*, vol. 159, pp. 123–135, 2019.

[29] J. Liang, A. U. Chaudhry, and H. Yanikomeroglu, "Phasing parameter analysis for satellite collision avoidance in starlink and kuiper constellations," in *2021 IEEE 4th 5G World Forum (5GWF)*. IEEE, 2021, pp. 493–498.

[30] M. Werner, "A dynamic routing concept for atm-based satellite personal communication networks," *IEEE journal on selected areas in communications*, vol. 15, no. 8, pp. 1636–1648, 1997.

[31] 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*, 2020, pp. 205–211.

[32] U. Dharmaratna, H. Tsunoda, N. Kato, and Y. Nemoto, "A satellite selection method for walker delta LEO satellite networks," *IEICE transactions on communications*, vol. 87, no. 8, pp. 2124–2131, 2004.

[33] Y. Su, Y. Liu, Y. Zhou, J. Yuan, H. Cao, and J. Shi, "Broadband LEO satellite communications: Architectures and key technologies," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 55–61, 2019.

[34] Q. Chen, G. Giambene, L. Yang, C. Fan, and X. Chen, "Analysis of inter-satellite link paths for LEO mega-constellation networks," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 3, pp. 2743–2755, 2021.

[35] H. Li and X. Gu, "Adaptive atm routing in walker delta satellite communication networks," in *2006 1st International Symposium on Systems and Control in Aerospace and Astronautics*. IEEE, 2006, pp. 6–pp.

[36] C.-J. Wang, "Structural properties of a low Earth orbit satellite constellation-the walker delta network," in *Proceedings of MILCOM'93-IEEE Military Communications Conference*, vol. 3. IEEE, 1993, pp. 968–972.

[37] S. C. Burleigh and E. J. Birrane, "Toward a communications satellite network for humanitarian relief," in *1st International Conference on Wireless Technologies for Humanitarian Relief*, 2011, pp. 219–224.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101008233.

[38] M. Feldmann, J. A. Fraire, F. Walter, and S. C. Burleigh, "Ring road networks: Access for anyone," *IEEE Communications Magazine*, vol. 60, no. 4, pp. 38–44, 2022.

[39] C. Krupiarz, C. Belleme, D. Gherardi, and E. Birrane, "Using smallsats and DTN for communication in developing countries," in *Proc. International Astronautical Congress (IAC-08. B4. 1.8)*, 2008.

[40] J. A. Fraire, M. Feldmann, and S. C. Burleigh, "Benefits and challenges of cross-linked ring road satellite networks: A case study," in *2017 IEEE ICC*. IEEE, 2017, pp. 1–7.

[41] M. Feldmann and F. Walter, "Refining the ring road-delays and path lengths in a LEO satellite message-ferry network," in *2017 IEEE ICC*. IEEE, 2017, pp. 1–7.

[42] M. Feldmann, J. A. Fraire, and F. Walter, "Tracking lunar ring road communication," in *2018 IEEE International Conference on Communications (ICC)*. IEEE, 2018, pp. 1–7.

[43] F. Walter, "Prediction-enhanced Routing in Disruption-tolerant Satellite Networks," Doctoral dissertation, Technische Universität Dresden, 2020.

[44] M. Cello, M. Marchese, and F. Patrone, "Hot spot selection in rural access nanosatellite networks," in *Proceedings of the 9th ACM MobiCom workshop on Challenged networks*, 2014, pp. 69–72.

[45] M. Marchese and F. Patrone, "E-CGR: Energy-aware contact graph routing over nanosatellite networks," *IEEE Transactions on Green Communications and Networking*, vol. 4, no. 3, pp. 890–902, 2020.

[46] Q. Xiaogang, M. Jiulong, W. Dan, L. Lifang, and H. Shaolin, "A survey of routing techniques for satellite networks," *Journal of communications and information networks*, vol. 1, no. 4, pp. 66–85, 2016.

[47] M. A. A. Madni, S. Iranmanesh, and R. Raad, "DTN and non-DTN routing protocols for inter-cubesat communications: A comprehensive survey," *Electronics*, vol. 9, no. 3, p. 482, 2020.

[48] H. Yan, Q. Zhang, and Y. Sun, "A novel routing scheme for LEO satellite networks based on link state routing," in *2014 IEEE 17th International Conference on Computational Science and Engineering*. IEEE, 2014, pp. 876–880.

[49] H. S. Chang, B. W. Kim, C. G. Lee, S. L. Min, Y. Choi, H. S. Yang, D. N. Kim, and C. S. Kim, "FSA-based link assignment and routing in low-Earth orbit satellite networks," *IEEE transactions on vehicular technology*, vol. 47, no. 3, pp. 1037–1048, 1998.

[50] B. Jianjun, L. Xicheng, L. Zexin, and P. Wei, "Compact explicit multi-path routing for LEO satellite networks," in *HPSR. 2005 Workshop on High Performance Switching and Routing, 2005.* IEEE, 2005, pp. 386–390.

[51] T. Taleb, D. Mashimo, A. Jamalipour, K. Hashimoto, Y. Nemoto, and N. Kato, "Sat04-3: Elb: an explicit load balancing routing protocol for multi-hop ngeo satellite constellations," in *IEEE Globecom 2006*. IEEE, 2006, pp. 1–5.

[52] G. Suvarna and R. Chandrashekhar, "Study of load balancing routing algorithm for low Earth orbit satellite networks," *Int. J. Innov. Appl. Stud*, vol. 11, pp. 198–205, 2014.

[53] Ö. Korçak, F. Alagöz, and A. Jamalipour, "Priority-based adaptive routing in ngeo satellite networks," *International journal of communication systems*, vol. 20, no. 3, pp. 313–333, 2007.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101008233.

[54] H. Tan and L. Zhu, "A novel routing algorithm based on virtual topology snapshot in LEO satellite networks," in *2014 IEEE 17th International Conference on Computational Science and Engineering*. IEEE, 2014, pp. 357–361.

[55] S. Karapantazis, E. Papapetrou, and F.-N. Pavlidou, "On-demand routing in LEO satellite systems," in *2007 IEEE International Conference on Communications*. IEEE, 2007, pp. 26–31.

[56] E. Papapetrou, S. Karapantazis, and F.-N. Pavlidou, "Distributed on-demand routing for LEO satellite systems," *Computer networks*, vol. 51, no. 15, pp. 4356–4376, 2007.

[57] E. Ekici, I. F. Akyildiz, and M. D. Bender, "Datagram routing algorithm for LEO satellite networks," in *Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No. 00CH37064)*, vol. 2. IEEE, 2000, pp. 500–508.

[58] ——, "A distributed routing algorithm for datagram traffic in LEO satellite networks," *IEEE/ACM Transactions on networking*, vol. 9, no. 2, pp. 137–147, 2001.

[59] X. Liu, X. Yan, Z. Jiang, C. Li, and Y. Yang, "A low-complexity routing algorithm based on load balancing for LEO satellite networks," in *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*. IEEE, 2015, pp. 1–5.

[60] X. Liu, Z. Jiang, C. Liu, S. He, C. Li, Y. Yang, and A. Men, "A low-complexity probabilistic routing algorithm for polar orbits satellite constellation networks," in *2015 IEEE/CIC International Conference on Communications in China (ICCC)*. IEEE, 2015, pp. 1–5.

[61] T.-H. Chan, B. S. Yeo, and L. Turner, "A localized routing scheme for LEO satellite networks," in *21st International Communications Satellite Systems Conference and Exhibit*, 2003, p. 2357.

[62] Y. Zhu, L. Qian, L. Ding, F. Yang, C. Zhi, and T. Song, "Software defined routing algorithm in LEO satellite networks," in *2017 International Conference on Electrical Engineering and Informatics (ICELTICs)*. IEEE, 2017, pp. 257–262.

[63] J. Jin, F. Tian, Z. Yang, H. Di, and G. Li, "A disruption tolerant distributed routing algorithm in LEO satellite networks," *Applied Sciences*, vol. 12, no. 8, p. 3802, 2022.

[64] M. Roth, H. Brandt, and H. Bischl, "Implementation of a geographical routing scheme for low Earth orbiting satellite constellations using intersatellite links," *International Journal of Satellite Communications and Networking*, vol. 39, no. 1, pp. 92–107, 2021.

[65] Q. Chen, X. Chen, L. Yang, S. Wu, and X. Tao, "A distributed congestion avoidance routing algorithm in mega-constellation network with multi-gateway," *Acta Astronautica*, vol. 162, pp. 376–387, 2019.

[66] Y. Lu, Y. Zhao, F. Sun, H. Li, and D. Wang, "Dynamic fault-tolerant routing based on FSA for LEO satellite networks," *IEEE Transactions on computers*, vol. 62, no. 10, pp. 1945–1958, 2012.

[67] J. Bai, X. Lu, Z. Lu, and W. Peng, "A distributed hierarchical routing protocol for non-geo satellite networks," in *Workshops on Mobile and Wireless Networking/High Performance Scientific, Engineering Computing/Network Design and Architecture/Optical Networks Control and Management/Ad Hoc and Sensor Networks/Compil*. IEEE, 2004, pp. 148–154.

[68] M. Mohorcic, M. Werner, A. Svigelj, and G. Kandus, "Adaptive routing for packet-oriented intersatellite link networks: performance in various traffic scenarios," *IEEE Transactions on Wireless Communications*, vol. 1, no. 4, pp. 808–818, 2002.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101008233.

[69] M. Mohorcic, A. Svigelj, and G. Kandus, "Traffic class dependent routing in ISL networks," *IEEE transactions on aerospace and electronic systems*, vol. 40, no. 4, pp. 1160–1172, 2004.

[70] A. Svigelj, M. Mohorcic, and G. Kandus, "Oscillation suppression for traffic class dependent routing in ISL network," *IEEE transactions on aerospace and electronic systems*, vol. 43, no. 1, pp. 187–196, 2007.

[71] J. A. Fraire, O. De Jonckere, and S. C. Burleigh, "Routing in the space internet: a contact graph routing tutorial," *Journal of Network and Computer Applications*, vol. 174, p. 102884, 2021.

[72] R. Diana, E. Lochin, L. Franck, C. Baudoin, E. Dubois, and P. Gelard, "A DTN routing scheme for quasi-deterministic networks with application to LEO satellites topology," in *2012 IEEE Vehicular Technology Conference (VTC Fall)*, September 2012, pp. 1–5.

[73] S. Burleigh, "Dynamic routing for delay-tolerant networking in space flight operations," in *SpaceOps 2008 Conference*, 2008, p. 3406.

[74] ——, "Contact graph routing, IETF-Draft draft-burleigh-dtnrg-cgr-00," December 2009.

[75] ——, "Contact graph routing, IETF-Draft draft-burleigh-dtnrg-cgr-01," July 2010.

[76] ——, "Interplanetary overlay network: An implementation of the DTN bundle protocol," 2007.

[77] E. J. Birrane, "Improving graph-based overlay routing in delay tolerant networks," in *2011 IFIP Wireless Days (WD)*. IEEE, 2011, pp. 1–6.

[78] E. J. B. III, "Building routing overlays in disrupted networks: inferring contacts in challenged sensor internetworks," *International Journal of Ad Hoc and Ubiquitous Computing*, vol. 11, no. 2-3, pp. 139–156, 2012.

[79] E. Birrane, "Contact graph routing extension block," Internet RFC, Internet Draft, October 2013. [Online]. Available: https://tools.ietf.org/id/draft-irtf-dtnrg-cgreb-00.txt

[80] J. Segui, E. Jennings, and S. Burleigh, "Enhancing contact graph routing for delay tolerant space networking," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, December 2011, pp. 1–6.

[81] E. Birrane, S. Burleigh, and N. Kasch, "Analysis of the contact graph routing algorithm: Bounding interplanetary paths," *Acta Astronautica*, vol. 75, pp. 108 – 119, 2012.

[82] C. Caini, H. Cruickshank, S. Farrell, and M. Marchese, "Delay- and Disruption-Tolerant Networking (DTN): An Alternative Solution for Future Satellite Networking Applications," *Proceedings of the IEEE*, vol. 99, no. 11, pp. 1980–1997, November 2011.

[83] C. Caini and R. Firrincieli, *DTN for LEO Satellite Communications*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 186–198. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-23825-3_18

[84] ——, "Application of contact graph routing to LEO satellite DTN communications," in *2012 IEEE International Conference on Communications (ICC)*, June 2012, pp. 3301–3305.

[85] Z. Laitao, L. Yong, Z. Junxiang, W. Jing, T. Xiao, and Z. Jianguo, "Application of contact graph routing in satellite delay tolerant networks," *Chinese Journal of Space Science*, vol. 35, no. 1, pp. 116–125, 2014.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101008233.

[86] J. A. Fraire, P. G. Madoery, J. M. Finochietto, P. Ferreyra, and R. Velazco, "Internetworking approaches towards along-track segmented satellite architectures," in *Wireless for Space and Extreme Environments (WiSEE), 2016 IEEE International Conference on*, October 2016, in Press.

[87] M. Marchese and F. Patrone, "A source routing algorithm based on CGR for DTN-nanosatellite networks," in *GLOBECOM 2017-2017 IEEE Global Communications Conference*. IEEE, 2017, pp. 1–6.

[88] C. Krupiarz, C. Belleme, D. Gherardi, and E. Birrane, "Using smallsats and DTN for communication in developing countries," in *Proc. International Astronautical Congress (IAC-08. B4. 1.8)*, 2008.

[89] S. C. Burleigh and E. J. Birrane, "Toward a communications satellite network for humanitarian relief," in *Proceedings of the 1st International Conference on Wireless Technologies for Humanitarian Relief*, ser. ACWR '11. New York, NY, USA: ACM, 2011, pp. 219–224. [Online]. Available: http://doi.acm.org/10.1145/2185216.2185280

[90] J. A. Fraire, M. Feldmann, and S. C. Burleigh, "Benefits and challenges of cross-linked ring road satellite networks: A case study," in *2017 IEEE International Conference on Communications (ICC)*, 2017, pp. 1–7.

[91] M. Feldmann, J. A. Fraire, and F. Walter, "Tracking lunar ring road communication," in *2018 IEEE International Conference on Communications (ICC)*, May 2018, pp. 1–7.

[92] N. Bezirgiannidis, C. Caini, D. D. P. Montenero, M. Ruggieri, and V. Tsaoussidis, "Contact graph routing enhancements for delay tolerant space communications," in *2014 7th Advanced Satellite Multimedia Systems Conf. and the 13th Signal Processing for Space Comms. Workshop (ASMS/SPSC)*, September 2014, pp. 17–23.

[93] N. Bezirgiannidis, C. Caini, and V. Tsaoussidis, "Analysis of contact graph routing enhancements for DTN space communications," *Int. Journal of Satellite Coms. and Networking*, vol. 34, no. 5, pp. 695–709, 2016.

[94] J. A. Fraire, P. Madoery, and J. M. Finochietto, "Leveraging routing performance and congestion avoidance in predictable delay tolerant networks," in *Wireless for Space and Extreme Environments (WiSEE), 2014 IEEE International Conference on*, October 2014, pp. 1–7.

[95] J. A. Fraire, P. Madoery, J. M. Finochietto, and E. J. Birrane, "Congestion modeling and management techniques for predictable disruption tolerant networks," in *Local Computer Networks (LCN), 2015 IEEE 40th Conference on*, October 2015, pp. 544–551.

[96] G. Araniti, N. Bezirgiannidis, E. Birrane, I. Bisio, S. Burleigh, C. Caini, M. Feldmann, M. Marchese, J. Segui, and K. Suzuki, "Contact graph routing in DTN space networks: overview, enhancements and performance," *IEEE Communications Magazine*, vol. 53, no. 3, pp. 38–46, 2015.

[97] S. Burleigh, C. Caini, J. J. Messina, and M. Rodolfi, "Toward a unified routing framework for delay-tolerant networking," in *2016 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, 2016, pp. 82–86.

[98] G. Wang, S. C. Burleigh, R. Wang, L. Shi, and Y. Qian, "Scoping contact graph-routing scalability: Investigating the system's usability in space-vehicle communication networks," *IEEE Vehicular Technology Magazine*, vol. 11, no. 4, pp. 46–52, December 2016.

[99] P. Madoery, P. Ferreyra, J. Fraire, F. Gomez, J. Barrientos, and R. Velazco, "Enhancing Contact Graph Routing Forwarding Performance for Segmented Satellites Architectures," in *1st IAA Latin American Symposium on Small Satellites*, Argentina, March 2017.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101008233.

[100] P. G. Madoery, J. A. Fraire, F. D. Raverta, J. M. Finochietto, and S. C. Burleigh, "Managing Routing Scalability in Space DTNs," in *2018 6th IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, December 2018, pp. 177–182.

[101] N. Alesi, "Hierarchical Inter-Regional Routing Algorithm for Interplanetary Networks," Master's thesis, School of Engineering and Architecture, Department of Computer Science and Engineering, Bologna, Italy, 2018.

[102] J. A. Fraire, P. Madoery, S. Burleigh, M. Feldmann, J. Finochietto, A. Charif, N. Zergainoh, and R. Velazco, "Assessing contact graph routing performance and reliability in distributed satellite constellations," *Journal of Computer Networks and Communications*, vol. 2017, 2017.

[103] P. Madoery, F. Raverta, J. Fraire, and J. Finochietto, "On the performance analysis of disruption tolerant satellite networks under uncertainties," in *Proceedings of the 2017 XVII RPIC Workshop*, September 2017.

[104] P. G. Madoery, F. D. Raverta, J. A. Fraire, and J. M. Finochietto, "Routing in space delay tolerant networks under uncertain contact plans," in *2018 IEEE International Conference on Communications (ICC)*, May 2018, pp. 1–6.

[105] F. D. Raverta, R. Demasi, P. G. Madoery, J. A. Fraire, J. M. Finochietto, and P. R. D'Argenio, "A Markov Decision Process for Routing in Space DTNs with Uncertain Contact Plans," in *2018 6th IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, December 2018, pp. 189–194.

[106] P. R. D'Argenio, J. A. Fraire, and A. Hartmanns, "Sampling distributed schedulers for resilient space communication," in *NASA Formal Methods - 12th International Symposium, NFM 2020, Moffett Field, CA, USA, May 11-15, 2020, Proceedings (In Press)*, 2020.

[107] J. A. Fraire, P. G. Madoery, A. Charif, and J. M. Finochietto, "On route table computation strategies in delay-tolerant satellite networks," *Ad Hoc Networks*, vol. 80, pp. 31–40, 2018.

[108] O. De Jonckère, "Efficient contact graph routing algorithms for unicast and multicast bundles," in *2019 IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT)*, July 2019, pp. 87–94.

[109] S. Dhara, C. Goel, R. Datta, and S. Ghose, "CGR-SPI: A New Enhanced Contact Graph Routing for Multi-source Data Communication in Deep Space Network," in *2019 IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT)*, July 2019, pp. 33–40.

[110] Consultative Committee for Space Data Systems (CCSDS), "Schedule-aware bundle routing (SABR) (blue book, recommended standard CCSDS 734.3-B-1," https://public.ccsds.org/Pubs/734x3b1.pdf, July 2019.

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