Ring Road Networks: Access for Anyone

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***Abstract*—Several billion people currently lack reliable access to the Internet and, thus, to a tremendous source of knowledge. In this paper, we describe a field-tested communication approach combining CubeSat platforms and delay-tolerant networking (DTN) solutions to provide asynchronous connectivity to populations and regions that are underserved by the Internet. The resulting class of networks is known as ring road networks (RRN), a networking approach that is built on technology developed for the construction of a Solar System Internet. The necessary self-sufficiency of DTN nodes enables network access to be deployed incrementally at low cost, supporting communities that cannot be profitably served by Internet satellite constellations. We present the RRN architecture and evaluate the expected performance by means of simulations. Based on the latter, we discuss μD3TN: a lightweight and open-source DTN protocol stack for RRNs and other DTN classes. μD3TN has been flight-tested in ESA's OPS-SAT in low-Earth orbit (LEO) during December 2020 and May 2021. This work discusses the experiment results as we validated the RRN approach in concrete application use cases. The reported outcomes motivate a new application domain.**

***Index Terms*—Ring Road Networks, Delay-tolerant Networking, Contact Graph Routing**

I. Introduction

In its existing form, digital connectivity expansion is based on the goal of universal continuous connectivity. Indeed, underlying Internet technology looks more like a phone call than sending a letter: a client expects a server to reply immediately. We claim that the difficulty of profitably achieving this goal globally has been the core reason for having billions of unconnected or under-connected people across the globe. 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 will become impractical or impossible in such conditions, even with the best possible technologies.

The vision argued in this paper is that by developing the delay-tolerant networking (DTN) technologies required to construct a Solar System Internet, we have acquired the means to reduce inequality right here on our planet by connecting remote places where the deployment of Internet infrastructure is economically (or technically) infeasible.

The core construct derived from this vision is framed in the "ring road network" (RRN) concept. 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 be implemented with 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.

In this paper, we present the fundamentals of RRNs and the supporting research. Next, we use the results of simulations to assess the expected performance of RRNs. Our open-source DTN protocol implementation, named μD3TN, is then introduced and evaluated in the first in-orbit experiment of the RRN concept, utilizing ESA's OPS-SAT. Afterwards, we briefly examine the categories of applications that are suitable for communicating via RRNs and those that are not. Finally, we discuss the cost advantages of the RRN architecture and the integration of RRN services with Internet services that will be provided by the large LEO satellite constellations currently under construction.

II. Background

A. CubeSats in LEO

CubeSats are standardized nano-satellites initially developed for pedagogical purposes, designed in a context where historically each new space mission required a full re-engineering of space and ground systems. Due to the CubeSat standard's merits in providing a common nano-satellite deployment platform, it found wide adoption. At the time of writing, different form factors are commonly deployed, named after the number of *units* they are composed of, whereas a 1-unit (1U) CubeSat may have a maximum weight of 1.33 kilograms and dimensions of 10×10×11.35 centimeters. For example, 3U, 6U, and 12U CubeSat platforms are now popular in the industry. Additionally, commercial off-the-shelf components and launch opportunities for CubeSats are readily available. Typically deployed in LEO, CubeSats orbit below the altitude of 2000 km and exhibit trajectories that can be accurately predicted. With an orbital period of ≈90 minutes, a LEO satellite appears on one horizon and disappears over the other in typically less than 10 minutes. Depending on the latitude, any single LEO satellite will be usually visible from a given spot less than five times a day; obviously, increasing the number of satellites in the constellation increases the frequency of overflights at any single location.

B. Delay-tolerant Networks

Delay-tolerant networking (DTN) extends network functionality beyond the environment in which the Internet works well, to challenged environments in which, e.g., long signal propagation delays, arbitrary and intermittent interruptions or limited communication resources are present (see RFC 4838 for details of the architecture). DTNs are relevant in many application domains such as airborne, vehicular, and underwater networks. Maturing since the early 2000's, DTN provides the means for nodes to cope with link disruptions and delays. In order to deal with interrupted end-to-end paths, the core idea behind DTN is to transmit packets via a store-carry-and-forward principle. Thus, intermediate nodes may store packets until an appropriate next-hop node is available. The topologies of DTNs cannot be represented as regular (static) graphs; instead, the topologies are described via time-variant graphs. The appearing and disappearing edges of these graphs can be described as so-called *contacts*. A contact is a period of time during which two nodes are able to transfer data uni- or bidirectionally.

The Bundle Protocol (version 6 defined in RFC5050 or version 7, which is currently in IETF's standardization process) harnesses the DTN principles by introducing a dedicated "bundle layer". This layer is operating on top of different underlying protocols, which provide their service to the bundle layer via a shim layer called *convergence layer*. The Bundle Protocol implements fundamental DTN features such as custody transfer (version 6), fragmentation, quality of service, and deadlines [1]. A DTN node does not assume continuous end-to-end connectivity; instead, it utilizes persistent storage to survive waiting periods of seconds, minutes, or days during which one or more links in the end-to-end path are inoperable. Several DTN protocols, including the Bundle Protocol, are currently discussed and specified in IETF (for Internet standardization) and CCSDS (for space communications standardization).

DTN protocols have been validated in space (UK-DMC, DINET, JAXA, ISS) [1], but never as yet in the context of RRNs.

III. Ring Road Networks

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 [2] for details). Building upon the initial idea of combining small satellites and DTN presented in 2008 [3], the technological and scientific landscape in this context has shown major advances that favor the deployment of RRNs before the end of this decade [2], [4]–[7]. In contrast

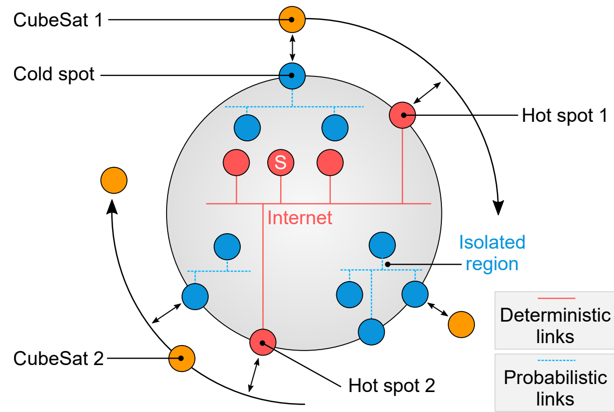

Fig. 1. RRN diagram. Nodes connected to the isolated *cold spot* can relay bundles to *cubesat 1*, which carries the data until flying over *hot spot 1*. The bundle can then reach the server on the Internet (*S*), which determines that the optimal return path is via *hot spot 2* and *cubesat 2*.

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 [2] 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. 1).

Responses are returned to cold spots, usually via other satellites, within minutes - or even hours.

Even an RRN comprising a single LEO satellite would enable users to run Wikipedia searches, receive remote medical assistance, and participate in global market stores, among many other services we are used to in urban environments. The only difference is that responses to ad-hoc queries might take minutes or hours to arrive; however, prior subscription to information sources that are known to be of future interest would enable queries to be satisfied by local interrogation of previously cached information and, thus, yield immediate results. Moreover, introducing additional satellites in the constellation will increase the frequency of all cold spot and hot spot overflights, hence, both reducing round-trip latency and increasing overall system capacity. We present a numerical assessment of the the expected performance for RRN satellite fleets of various configurations in Section IV.

A. Beneficiaries

One of the essential target beneficiaries of the RRN concept are unconnected populations, anywhere in the world, that are currently isolated because the deployment of synchronous connectivity infrastructure is not cost-justified. This can be either because the area is difficult to access (i.e., remote islands, mountain ranges, jungles) or because the area does not represent an attractive market (i.e., the world's poorest regions).

The nature of low-cost CubeSats and asynchronous DTN connectivity yields an infrastructure that is orders of magnitude cheaper than satellite Internet infrastructure, which maps to very low cost for the final user, sharply lowering the accessibility barrier. In particular, RRN programs are a perfect and realistic fit for governments' and humanitarian organizations' investments in providing free Internet connectivity to remote regions. Finally, the same infrastructure can be applied to benefit a plethora of business-oriented cases to reduce the cost of time-insensitive communications [2], including secure and low-data-rate secondary and backup channels for sensitive data.

B. Supporting Research

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

a) Taxonomy and Tools: A comprehensive taxonomy of RRNs has been presented in [5]. 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 [4]. 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* [8], [9], *DtnSim* based on *Omnet++* [4], *aiodtnsim* [7], and further custom toolchains (e.g., [6]).

b) Routing: 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 [6]. A Selection scheme for routing via specific hot spots was presented in [8] and further energy-aware routing schemes for RRN scenarios were explored in [9].

c) 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 [7]. 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.

IV. Evaluation

This section presents a quantitative assessment of a representative RRN scenario we have performed leveraging the *aiodtnsim* simulator described in [7].

We consider 10 randomly distributed ground stations served by 1, 5, 10, 15, and 20 satellites randomly selected from a set of 20 CubeSats (Two-Line Elements files obtained from Celestrak). Contacts between ground stations and satellites are considered viable when the elevation is equal to or higher than 10°. No ISLs are considered in this evaluation. A contact plan is computed for a scenario duration of 3 days (72 hours). Bundles of 2 MiB are generated for the initial 80% of the total scenario duration, from and to random ground stations. The bundle generation period is set to 1000 (seconds) divided by the number of satellites, with a standard deviation equal to half of the interval. Twenty runs are performed for each scenario with different transmission plans (i.e., varying source-destination pairs). Each node's buffer size is set to 2 GiB, and data rates are configured to 256 kbit/s (uplink) and 1 Mbit/s (downlink). A maximum of 5 concurrent links are allowed.

We evaluate the expected performance of RRN when bundles are routed using three categories of routing approaches. On the one hand, *Epidemic* routing forwards a copy of the bundle to each possible neighbor, up to a maximum of 6 hops. This is a trivial approach, with high delivery ratio and minimal computational cost, achieved at the expense of high resource consumption (memory and energy). *Spray and Wait* [10] is a more efficient replica-based scheme where a limited number of copies (6 in our case) are "spread" into the network, to then "wait" till one of these nodes meets the destination. In contrast, *CGR* exploits an adaptation of Dijkstra's algorithm to optimally deliver a single copy of the bundle via the fastest path [1]. To this end, a pre-computed contact plan is assumed to be available at every node in the RRN.

A. Results

Results are summarized in Fig. 2. In terms of delivery probability, results in Fig. 2-a) show that congestion due to multiple replicas in Epidemic prohibits adequate scalability. Indeed, although the maximum delivery ratio is obtained for 5 satellites, only 51.2% of the bundles are delivered for the 20 satellite case. We observe that Epidemic exhausts both satellite memory and contact capacity after 30, 40, and 50 hours for scenarios with 20, 15, and 10 satellites, respectively.

Spray And Wait improves on the delivery ratio of Epidemic due to the more efficient replication strategy, but CGR is notably the most efficient approach with a 100% delivery success for any fleet size. CGR also provides the optimal delivery delay (Fig. 2-b), as it leverages topological data from the contact plan. In particular, an average end-to-end delay of 7.7 hours (σ=4.5) for a single satellite is reduced to 1.3 hours (σ=0.9) for 20 satellites.

Epidemic and Spray And Wait solutions fail to consistently reduce delay for larger fleets. The energy efficiency (Fig. 2-c) is also optimal for CGR, as every transmission effort results in the successful delivery of the routed bundle as long as the contact plan data is accurate (i.e., no packets are dropped). Epidemic routing ranges from 11% to 4% (1 to 20 satellites), while Spray And Wait presents a consistent efficiency of 22% for any fleet size.

Finally, copy-based routing presents the highest memory demands (Fig. 2-d), which are required to store the required replicas ranging from 60 MiB to 1.97 GiB. CGR is the most efficient in terms of storage, occupying 6.2 to 11.4 MiB (σ=7.1 to 12.9) for the evaluated traffic shape.

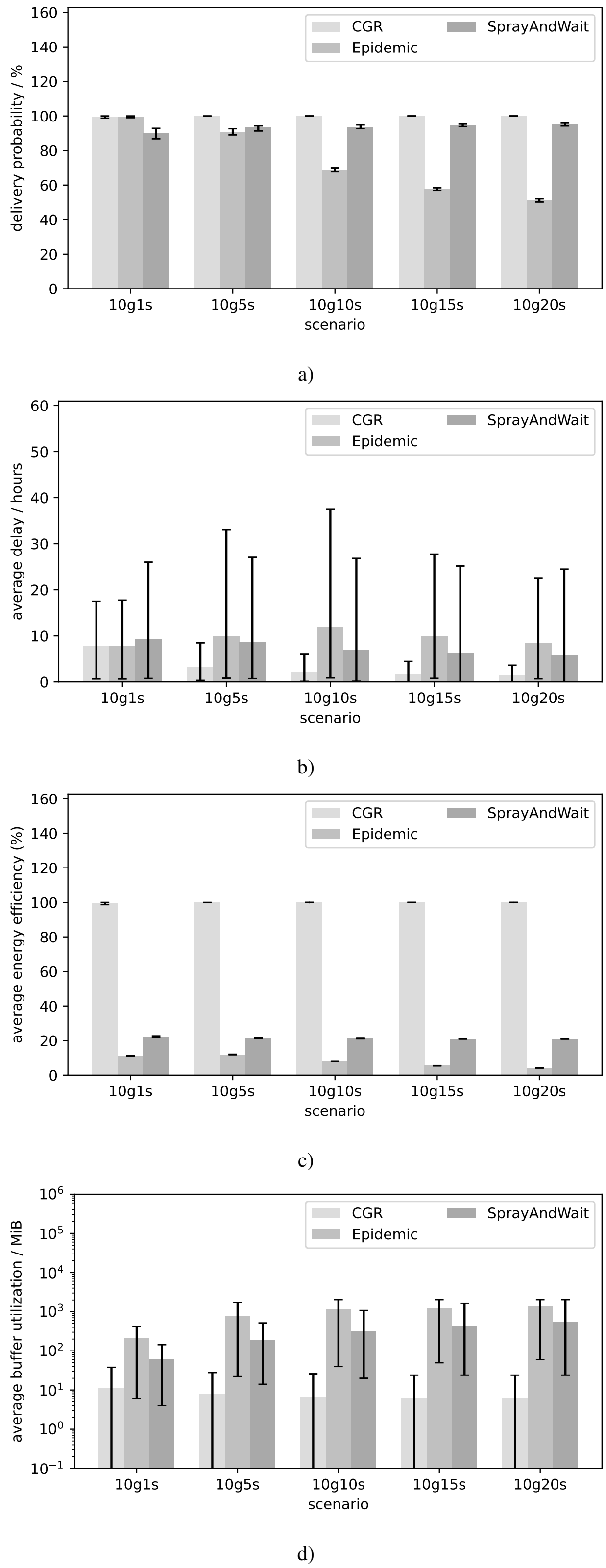

Fig. 2. RRN Evaluation results for scenarios with 10 ground stations (`10g`) served by 1 to 20 LEO satellites (`1s` to `20s`)

These evaluation results indicate that state-of-the-art DTN routing solutions exploiting the predictable nature of orbits could be deployed on cost-efficient nano-satellite platforms.

V. Implementation

To enable the flow of data in RRNs in the conditions identified by the simulations above, we developed Micro-DTN (μD3TN). μD3TN is an open-source lightweight DTN protocol implementation (https://gitlab.com/d3tn/ud3tn) written in the C programming language.

The software has a modular design that offers several convergence layer adapters (CLA) through which µD3TN can transport data over many different underlying network protocols. Additionally, integration with a wide variety of DTN applications is made possible by µD3TN's application agent protocol (AAP). It provides a simple, language-independent way for interacting with the DTN node. Furthermore, µD3TN implements a routing component (which includes a deterministic next-hop determination approach), contact management, and buffer management, among other features.

μD3TN was first validated in a challenged environment in the context of the COLDSUN project in cooperation with ESA in 2019, and was subsequently integrated into the OPS-SAT LEO satellite.

VI. In-Orbit Validation

The RRN proof of concept using μD3TN was validated on ESA's OPS-SAT during December 2020 and May 2021. Our goal with the OPS-SAT experiment was three-fold: (*i*) to show that the RRN concept can be applied in concrete LEO use cases; (*ii*) to flight-test the new version 7 of the DTN bundle protocol; and (*iii*) to evaluate µD3TN features in the RRN context.

A. OPS-SAT Overview

The OPS-SAT satellite is a three-unit CubeSat operated by ESA. It was launched in December 2019 and is equipped with a MityARM 5CSX board with a dual-core 800 MHz ARM processor.On top of this hardware, a Linux-based software stack launches and controls the experiments. A TCP interface is offered on the spacecraft for experiments to send/receive data to/from the communications subsystem of the satellite. The satellite's communication subsystem enables wireless packets in the Space Packet Protocol (SPP) format to be transferred via the OPS-SAT radio interface to the ground segment. μD3TN was adapted to utilize this TCP/SPP interface as a CLA. On the ground segment, the ground station at ESA's SMILE lab provides a similar TCP socket interface enabling us to connect our simulated hot and cold spots using a reverse SSH tunnel. Two major experiments were performed in this context.

B. Scenario 1: Web Services

The objective of the first experiment was to show that access to a web server from isolated cold spots is possible in an RRN scenario. For this experiment, we leverage the `curl` command-line tool to send an HTTP request to our µD3TN-based cold spot communication gateway (step 1 in Fig. 3). This instance then generates a bundle carrying the HTTP request (step 2) and sends it over the SPP CLA toward ESA's ground station (step 3). At the core of the setup, our *dispatcher* service provides a link that multiplexes to simulate different ground stations, even though we only connect to a single ground station from ESA. Based on a schedule, the packets are transmitted toward the ESA ground station (step 4), which then sends the bundle via its S-band radio uplink to the OPS-SAT (step 5). Onboard, we run another µD3TN instance, which processes and later forwards the received bundle via another downlink contact (step 6). Upon reception, the ground station then forwards the bundle again via the SSH tunnel to our dispatcher service (step 7), which sends it to the hot-spot instance, also running µD3TN (step 8). After unpacking the bundle's payload (step 9), the HTTP request is delivered to the webserver (step 10). The HTTP communication gateway then packs together the response in a bundle and returns it on a path equivalent to the one taken for the request.

We performed a simplified version of this test during our first test window in December 2020 and the full version of the test in May 2021. It was the first successful test of BPv7 in space, and it demonstrated that the μD3TN implementation can be used for the entire communication path, on the ground and on the satellite.

C. Scenario 2: Advanced Features

The goal of the second experiment, conducted in collaboration with the SPATIAM Corporation, was to demonstrate feature interoperability between different DTN protocol implementations within a scenario based on remote access to a Cloud service. In this context, μD3TN interacts with another DTN protocol implementation: Interplanetary Overlay Network (ION) [11], developed by the Jet Propulsion Laboratory, NASA. Here, ION is deployed in the hot spot element (see Fig. 3). (ION is the most complete and feature-rich DTN protocol stack. It interoperates with μD3TN, but its larger computational/memory footprint limits its applicability in processing-constrained CubeSats.) The user sends a picture to the Google Cloud Vision (GCV) API so that different features in the image may be identified, labeled, and reported back via the RRN. In the course of this experiment, we were able to test not only interoperability but also bundle fragmentation, as the large image file had to be split into multiple packets (bundles).

This test was performed successfully between the 21st to the 24th of May 2021. Due to COVID safety concerns, the experiment team could not sit together in a mission control room. The satellite connection was set up remotely to operate from a virtual machine via the SSH tunnel mechanism. The satellite's log files were evaluated in a video conference together with the ESA OPS-SAT team.

D. Outcomes

The most relevant outcome of the experiments is that the DTN protocols and our implementation of them in μD3TN worked without any serious issues. Additionally, we were able to show interoperability between ION and μD3TN, which worked well even when exercising advanced protocol features to support machine learning applications over RRNs.

There were also some challenges identified. Due to the large image files transmitted from the cold-spot, more than 200 packets per second were created, which provoked an overload on the CubeSat transmission system. To cope with this, ESA suggested introducing a rate-limit, which was finally set to 45 packets per second emitted by the μD3TN CLA at maximum to ensure a stable data flow. Also, additional packets destined for other subsystems of the satellite were received via the on-board socket connection, for which we had to implement a filtering mechanism so that not every packet would be interpreted as a DTN bundle.

Finally, the communication that we have performed was solely based on static time windows pre-configured on the satellite as well as on the ground segment. Once these time tags matched the local clocks, bundle transmissions were triggered. The first consequence of this is, of course, that we need very well-synchronized clocks. This is not an issue in OPS-SAT but might be for other spacecraft. Secondly, we had to make assumptions about whether a link is present, complicating debugging. Indeed, we cannot be entirely sure of an active link being available until having real feedback from the satellite. As a first workaround, we scheduled the contacts in such a way that they only occur when a satellite has a high elevation in relation to the ground station – thus, the probability is quite high that a connection will be present (for some contacts we only scheduled transmissions above 15°). Of course, this strategy reduces the amount of data that can be transferred. Additionally, we implemented a periodic ping-like trigger for our tests, which sends one bundle to the satellite, which is immediately returned and invokes the test run upon reception. This mechanism significantly improved the reliability of the experiment setup.

E. Next Steps

RRN challenges remain in evaluating the approach in larger systems, with larger hop-counts and with larger time spans. We plan to advance these aspects in further field tests planned for mid 2022. These will be carried on as part of the REDMARS project, funded by the federal Ministry of Education and Research of Germany. The goal is to transfer ideas from the recursive internetworking architecture (RINA) [12] to the DTN domain. Here, the challenge is to move from the conceptual to the concrete level by implementing recursive and scalable routing via bundle-in-bundle encapsulation (BIBE) and dedicated extension blocks. These will be validated in orbit – in the OPS-SAT mission, if still available, or on other similar platforms.

VII. Outlook

A. Applications

The vision of RRN frames the Internet as a special case of network communications, a constrained environment in which delay is insignificant and prolonged disruptions are considered a topological anomaly; RRN addresses a more general network

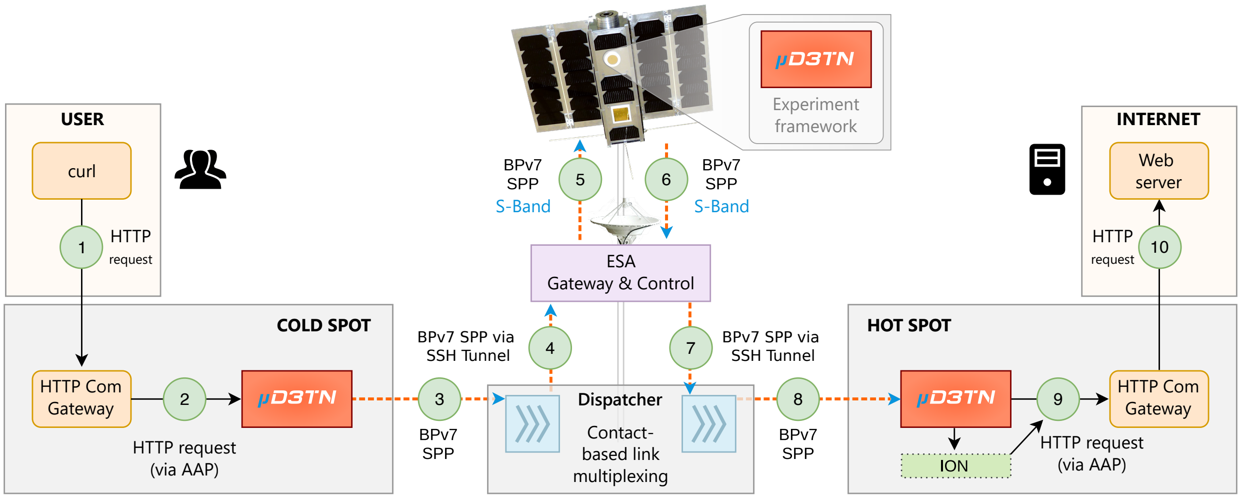

Fig. 3. OPS-SAT experiment set-up.

model in which long round-trip times slow down but do not impede end-to-end communications. The DTN network infrastructure is a necessary but not sufficient element of this model; applications themselves must be delay-tolerant.

Most types of communication fulfil this requirement. Though the massive use of synchronous real-time communication such as VoIP or Instant Messaging, oftentimes communication does not depend on ad-hoc availability of data at the moment of its creation. Accessing knowledge bases such as Wikipedia, watching movies streamed from a content distribution network (CDN), receiving weather forecast data, or transmitting backup information to a remote server - all these scenarios have in common that parts of the network between the initial data source and the destination are tolerant in regards to delays of even hours. In a large number of scenarios, delays are totally acceptable. More generally, emerging application technologies based on publish/subscribe operations, notably including information-centric networking [13], would be supported by RRN.

B. Satellite Broadband

It could be asserted that the global Internet access promised by upcoming constellations will render RRN unnecessary. However, because the DTN architecture on which RRN is based is designed to utilize underlying Internet services where they are available, expanded Internet service will extend the capabilities of an overlying RRN network; integration of the two technologies is not an obstacle.

More importantly, it remains possible that even these extremely large constellations will be unable to provide global network service at a price affordable for the world's least-advantaged populations. The three major competitors in satellite Internet deployment at this time are the Kuiper, Starlink, and OneWeb projects, with 3236, 4408, and 648 satellites, respectively. OneWeb projects the total cost of its constellation to be between \$5.5 billion and \$7 billion. Optimistically guessing the correct figure to be \$6 billion, we obtain a mean cost per satellite of about \$9 million. This suggests that the total cost of deploying the Kuiper constellation would be about \$30 billion, and the total cost of deploying the Starlink constellation would be about \$40 billion; the total cost of the three constellations would then be approximately \$76 billion.

According to ABI Research [14], the total market for satellite broadband currently comprises 3.6 million subscribers and is projected to increase at about 8% per year, reaching 7.56 million users by 2031. Assuming all three providers remain in operation at that time, the deployment cost per subscriber will have been just over \$10,000. In order to amortize that cost, monthly service charges would exceed the resources of many potential users in economically-disadvantaged regions. For example, Starlink beta subscribers are currently charged \$99/month.

A further consideration is the extension of terrestrial broadband. Outside of populated and relatively affluent areas, particularly cities, satellite broadband is the only available option; however, the proportion of the world's population that resides in cities is projected to increase from 55% to over 66% by 2050, see [15]. The relative demand for satellite broadband may decrease over time.

In short, we suggest that RRN may emerge as a better cost-justified answer to the problem of providing network communication service to the economically or geographically disadvantaged.

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Juan A. Fraire is researcher at INRIA/CONICET, and associate professor at Universidad Nacional de Córdoba (UNC) and Saarland University in Germany. His research focuses on space networking and applications. Juan is the founder and chair of the STINT Workshop, has co-authored more than 60 papers and collaborates with world-renowned space agencies and companies.

Felix Walter is CTO of D3TN GmbH. He received a doctorate degree in the area of DTN in 2020 and holds a Diploma degree in information systems engineering (2016). He promotes the goal of providing reliable connectivity in the most challenging environments by steering the technical development of the company and its products.

Scott Burleigh recently retired from a position as Principal Engineer at the Jet Propulsion Laboratory, California Institute of Technology, where he had been developing flight mission software since 1986. Mr. Burleigh co-authored and leaded the specification for version 6 and 7 of the DTN Bundle Protocol.