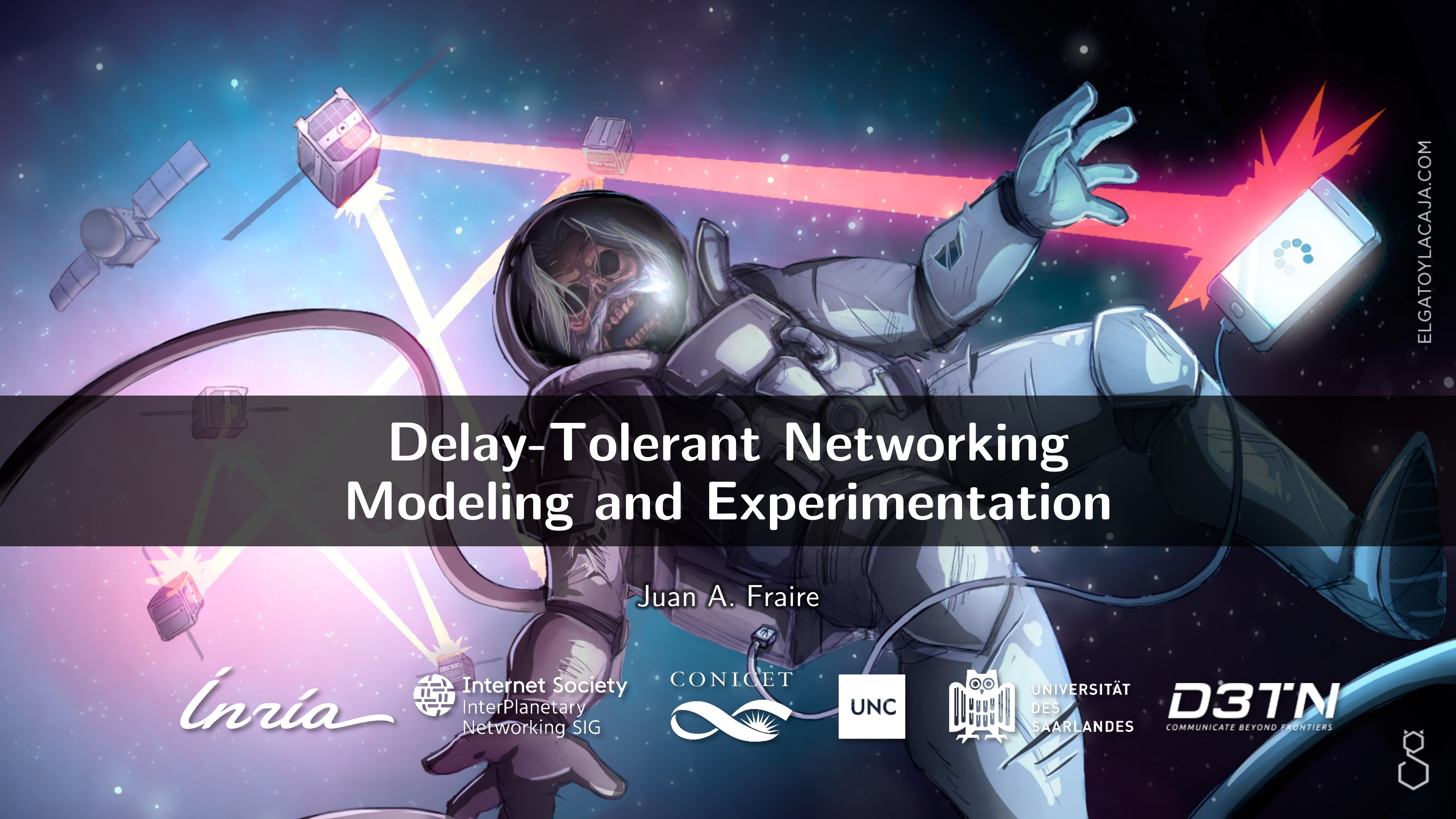

Delay-Tolerant Networking Modeling and Experimentation

Juan A. Fraire

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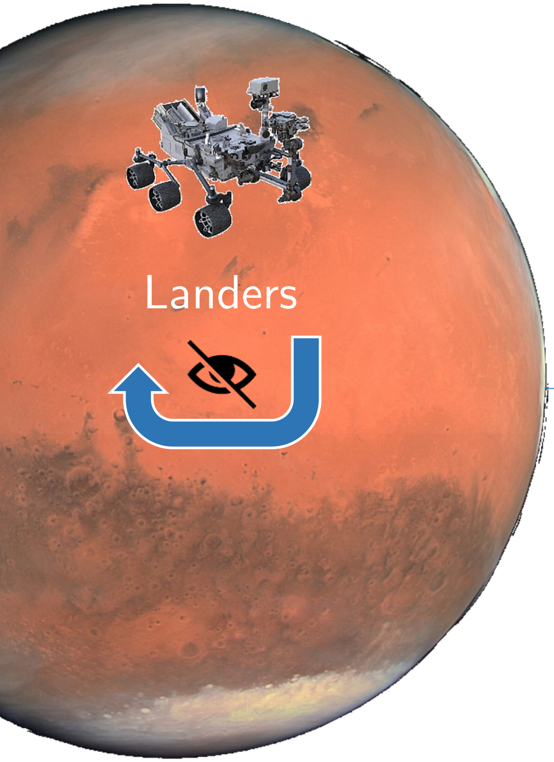
CONICET
UNC
UNIVERSITÄT DES SAARLANDES
D3TN COMMUNICATE BEYOND FRONTIERS

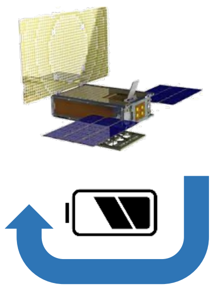
Agenda

- **Motivation**
  - **Interplanetary Internet**
- Architecture
  - Delay-Tolerant Networking
- Modeling
  - Structures and Algorithms
- Experiments
  - ColdSun and RedMars

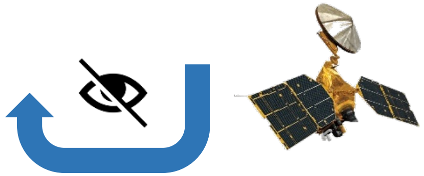
Motivation

Interplanetary Internet



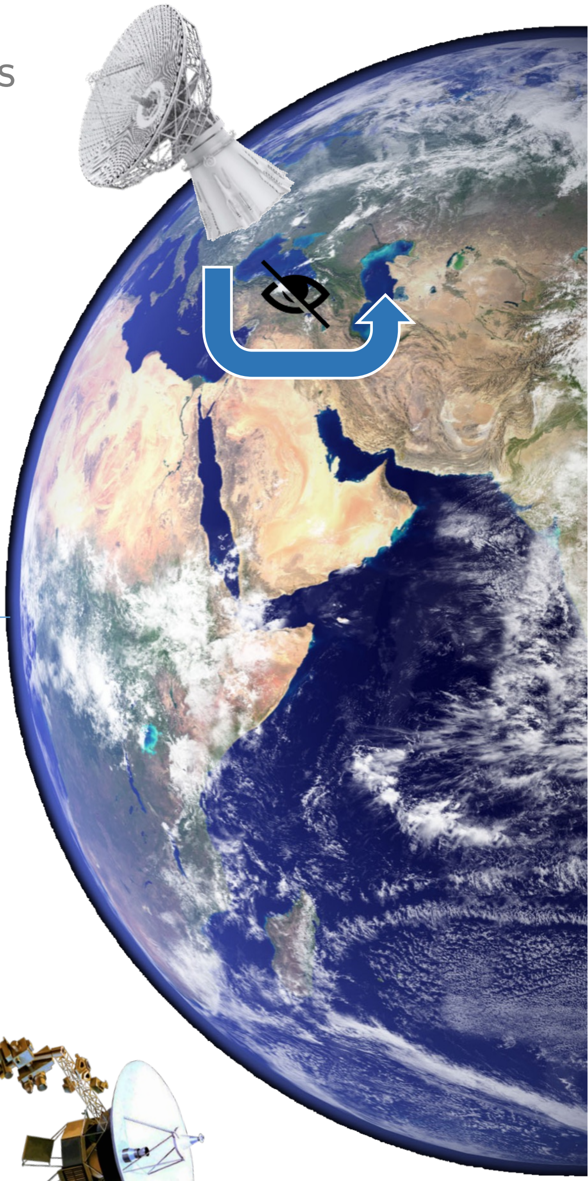


CubeSats



Orbiters

NASA's DSN



Comms performance decreases as the square of the distance

GEO: ~40,000km
Mars: ~400,000,000km

100 million times weaker

min 3.1 min

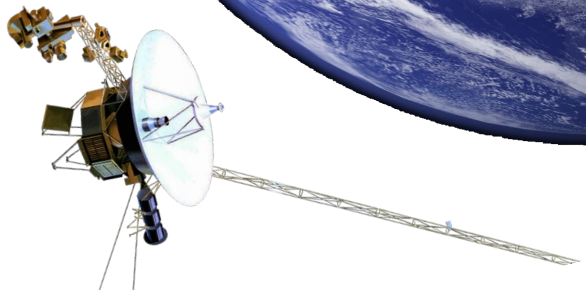
avg **12.5 min** *owlt*

max 22.4 min

Control Flow? DNS Lookup? Ping?

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
AU	0,38	0.72	1.00	1.52	5.21	9.54	19.18	30.11
	3 min	6 min	8 min	**12 min**	43 min	1h20	2h40	4h10

Voyager 1: 154 AU, 21:30 hrs.
Voyager 2: 128 AU, 17:51 hrs.



IPNSIG

ipnsig.org

Agenda

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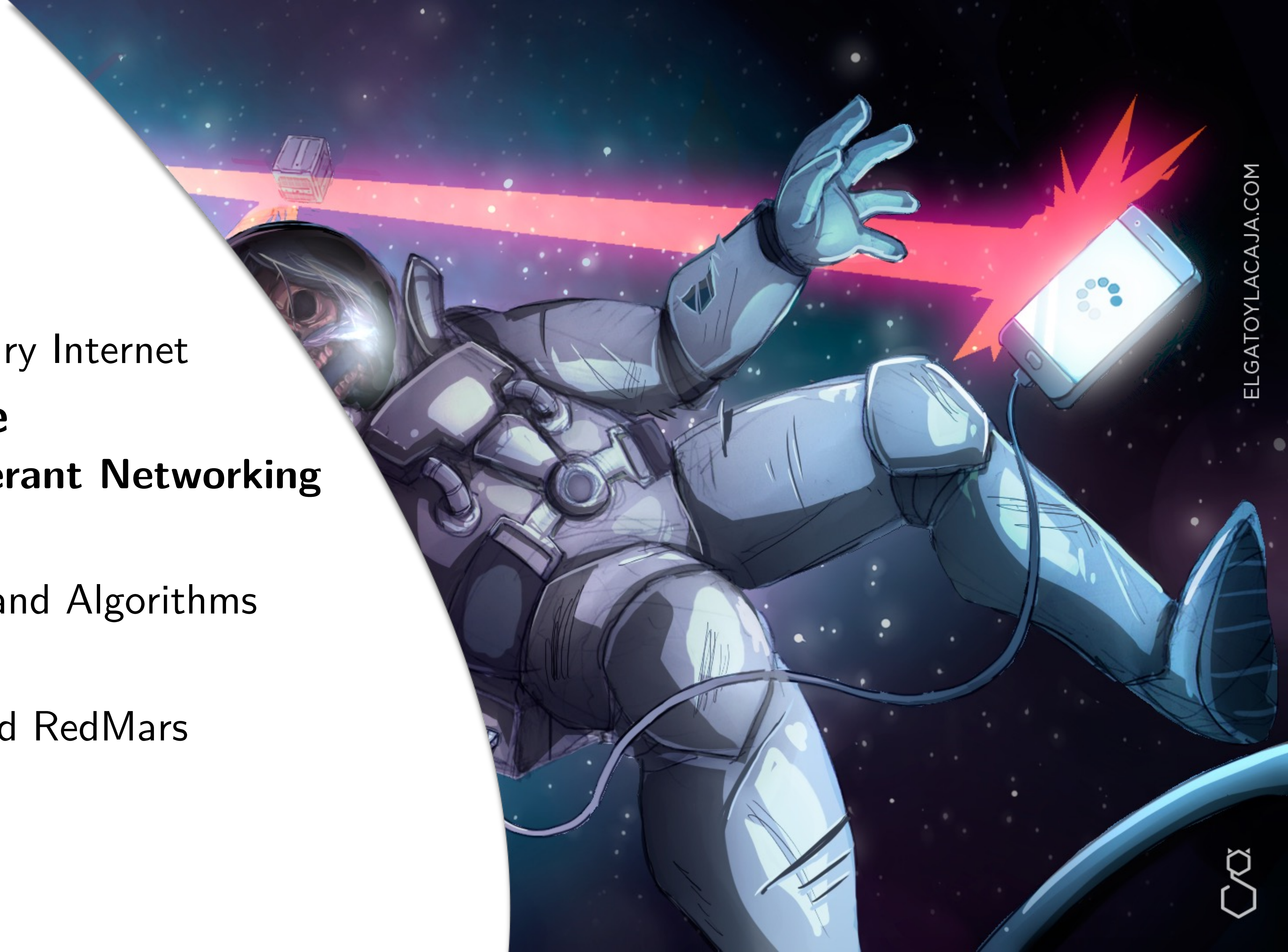


Delay-Tolerant Networking

Data Handling Approach

Traditional Internet (**TCP**)

Instantaneous flow
of information

Delay-Tolerant Networking (**DTN**)

Delay and disruptions
Storage of data

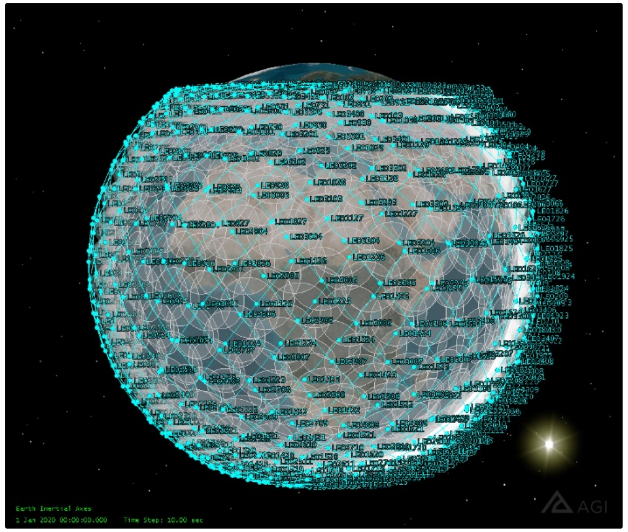
Telephony model

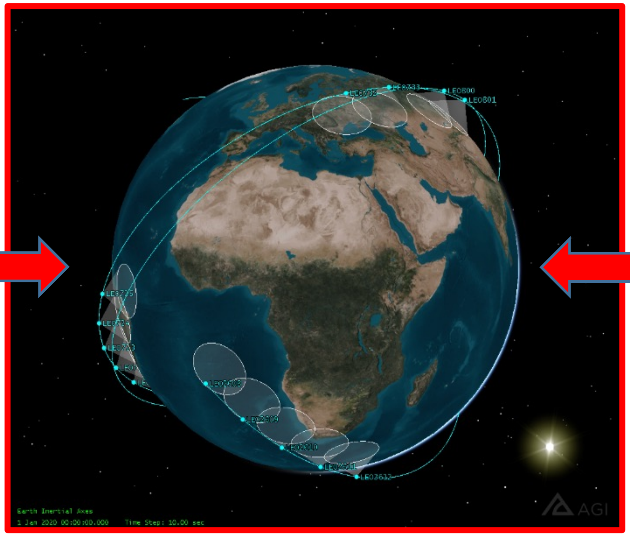
PEPs

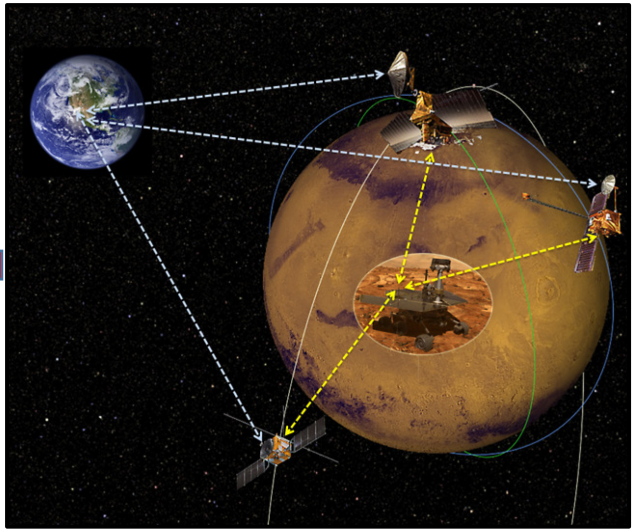
Sparse Constellations
Ring Road Networks

Epistolary model

Synchronous







Asynchronous

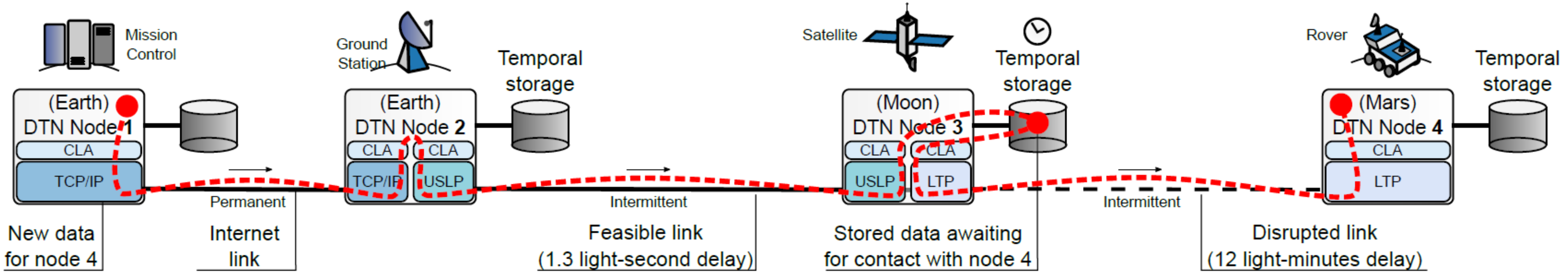
[1] Fall, Kevin. "A delay-tolerant network architecture for challenged internets." Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications. 2003.

Delay-Tolerant Networking

Architecture and Protocols

- Core Principles
  - Store-carry-and-forward
  - Reduced end-to-end messaging
- DTN Architecture → Bundle Protocol
  - Persistent storage (!= buffering)
  - Bundle features: blocks, custody, fragmentation, deadline

- RFC 4838
- RFC 9171 (5050)
- CCSDS BP
- CCSDS BPSec
- CCSDS LTP
- CCSDS SABR



[1] Scott, Keith, and Scott Burleigh. Bundle protocol specification. No. rfc5050. 2007. and No. rfc 9171. 2022.

Delay-Tolerant Networking

Concept of Operation

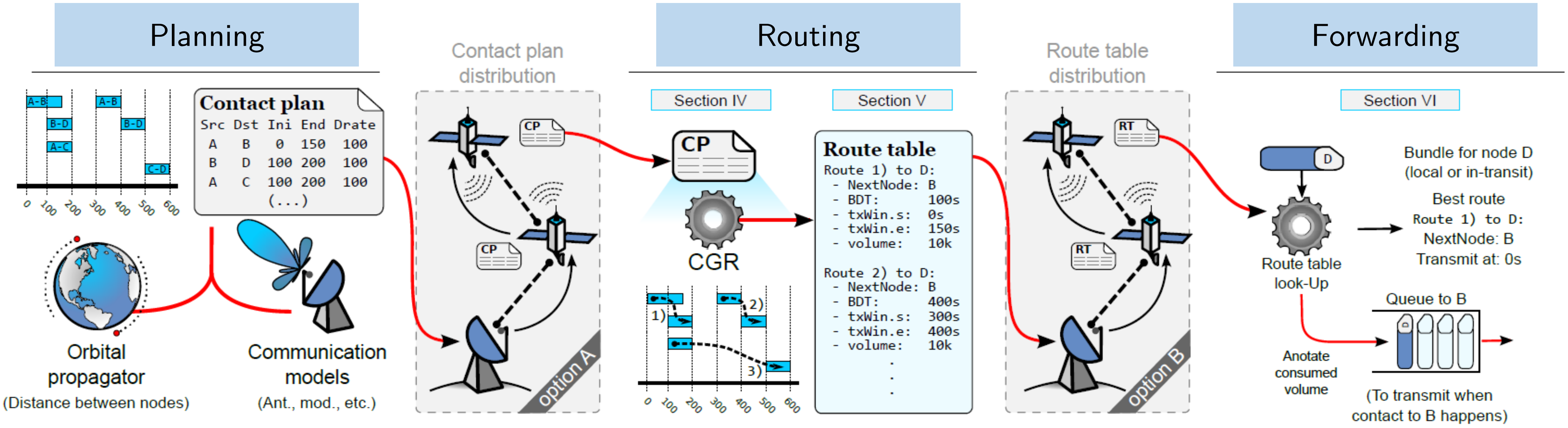
Strongly time-decoupled

Planning: computation of the *contact plan*

Routing: *path* computation from the contact plan

Forwarding: *path* selection and *queuing*

Path: *when* and to *which* neighbor



[1] Fraire, Juan A., Olivier De Jonckère, and Scott C. Burleigh. "Routing in the space internet: A contact graph routing tutorial." Journal of Network and Computer Applications 174 (2021): 102884.

Agenda

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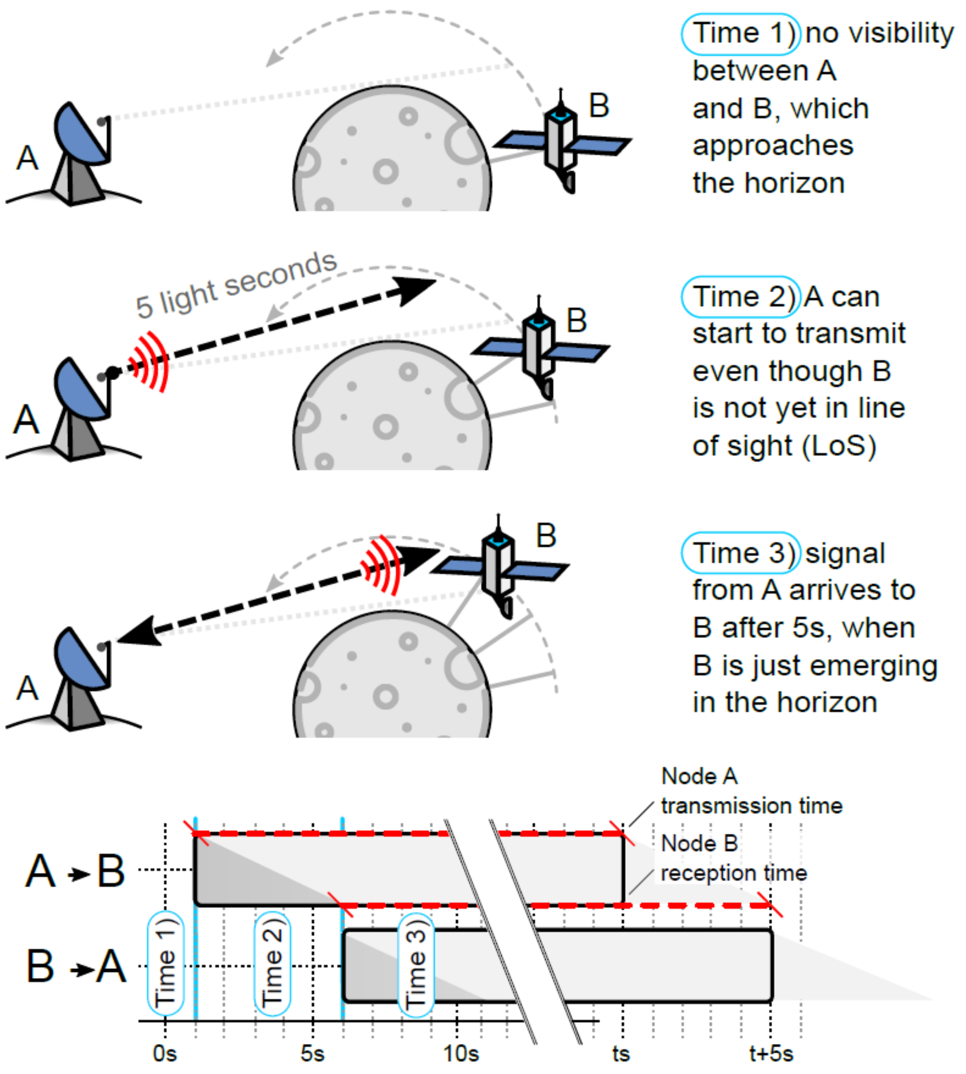
Modeling

Contact

- A contact $C_{A,B}^{t1,t2}$
  - A time interval $(t1;\ t2)$
  - Data will be transmitted by node A , at a data rate R $\rightarrow$ volume
  - That data will be received by node B, after one-way light time ($owlt$)
- Contacts are unidirectional
  - $\neq$ forward and return data rates
  - Due to $owlt$, the start time of a contact in one direction is typically **not** the same in the reverse channel

Possibly variable data rate



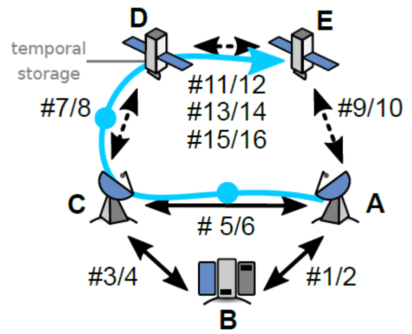
[1] Fraire, Juan A., Olivier De Jonckère, and Scott C. Burleigh. "Routing in the space internet: A contact graph routing tutorial." Journal of Network and Computer Applications 174 (2021): 102884.

Modeling

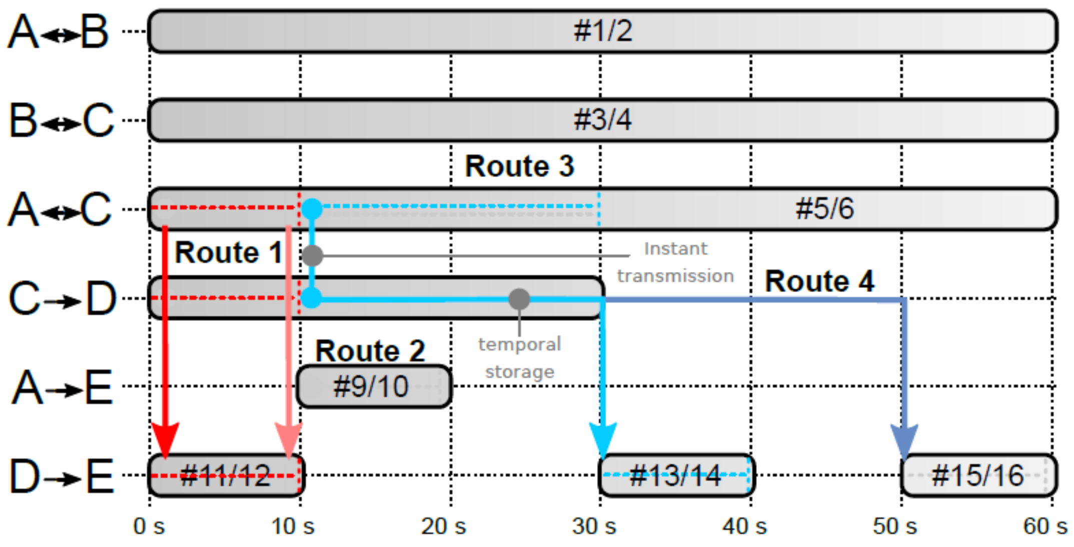
Contact Plan

- Contact plans capture the time-evolving nature of the network

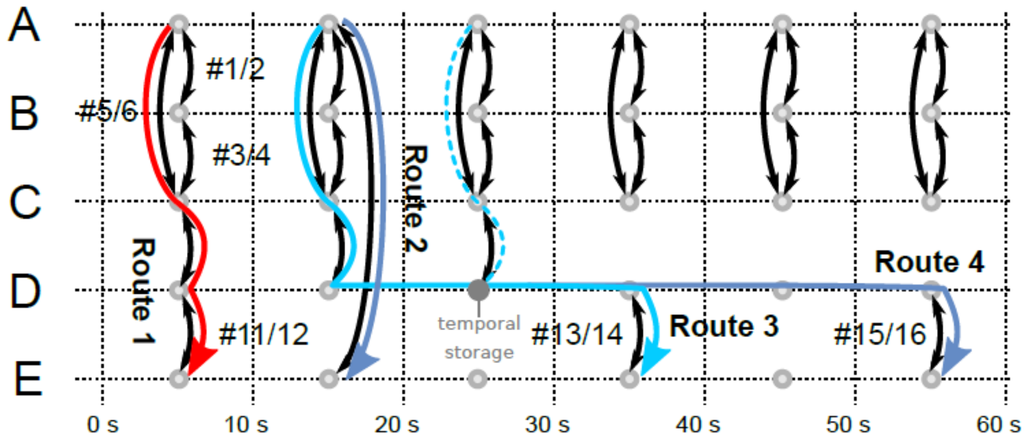
#	src	dst	st	end	rate	owlt
1/2	A	B	0	60	1	1
3/4	B	C	0	60	1	1
5/6	A	C	0	60	1	1
7/8	C	D	0	30	1	1
9/10	A	E	10	20	1	1
11/12	D	E	0	10	1	1
13/14	D	E	30	40	1	1
15/16	D	E	50	60	1	1



Timeline view



Time Evolving Graph (TEG)



Scales poorly (nodes, contacts, time)

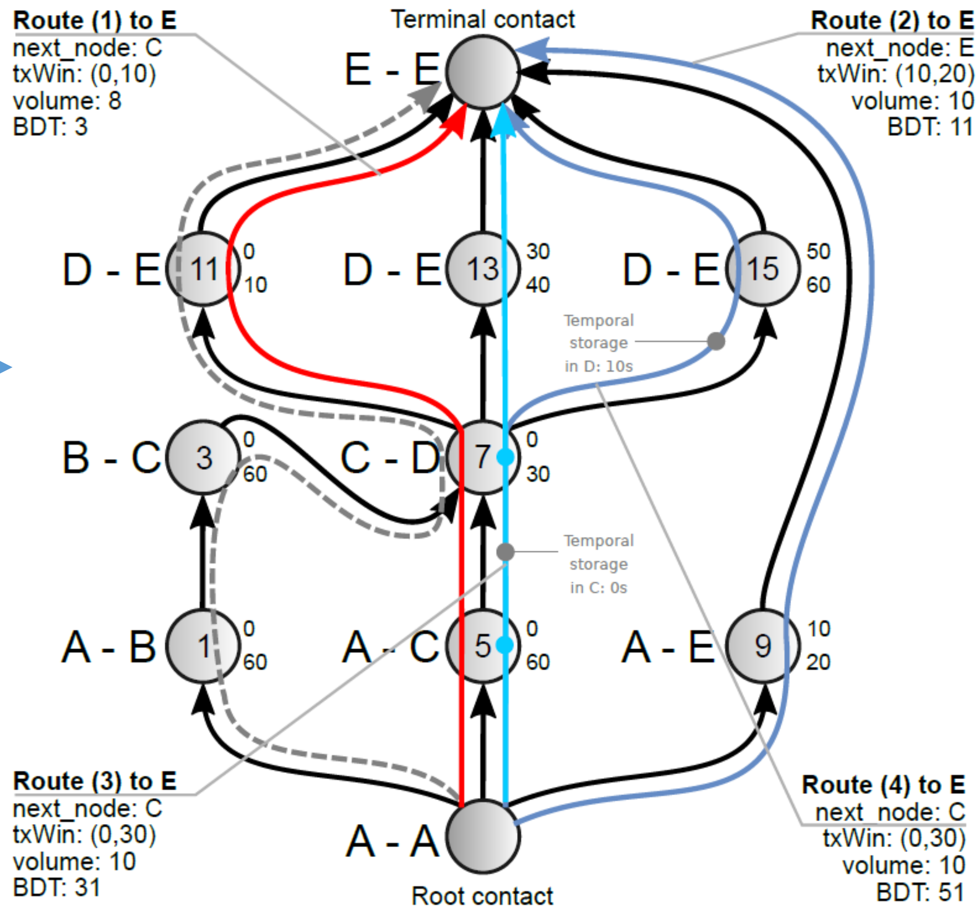
[1] Fraire, Juan A., Olivier De Jonckère, and Scott C. Burleigh. "Routing in the space internet: A contact graph routing tutorial." Journal of Network and Computer Applications 174 (2021): 102884.

Modeling

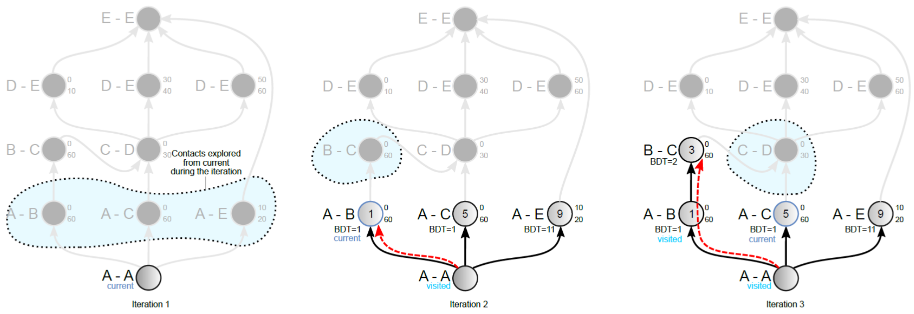
Routing

- *Multi-Graph*
  - Nodes with multiple timed edges
    - Edges E are episodes of contact
    - Vertices V are episodes of data retention
- *Contact graph*
  - Destination node D, Source node S
    - Edges E are episodes of data retention
    - Vertices V are episodes of contact

Directed acyclic graph
$CG_{DS} = (V; E)$



Shortest path algorithms

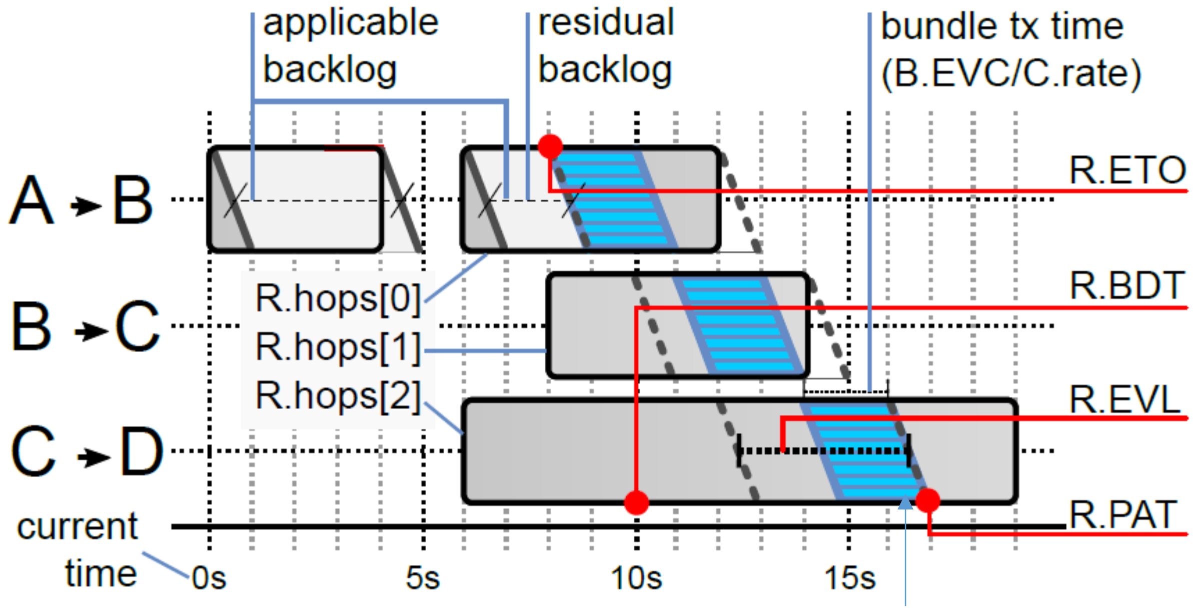


[1] Fraire, Juan A., Olivier De Jonckère, and Scott C. Burleigh. "Routing in the space internet: A contact graph routing tutorial." Journal of Network and Computer Applications 174 (2021): 102884.

Modeling

Forwarding

- Candidate route list created
  - Forwarding of local/in-transit bundle



Route volume

- Candidate route metrics
  - Best Delivery Time (BDT)
    - Deadline check
  - Earliest *tx* opportunity (ETO)
    - Queue backlog
  - Projected arrival time (PAT)
    - Transmission time $\forall\, R.hops$
  - Effective volume limit (EVL)
    - Lowest $EVL \in R.hops$

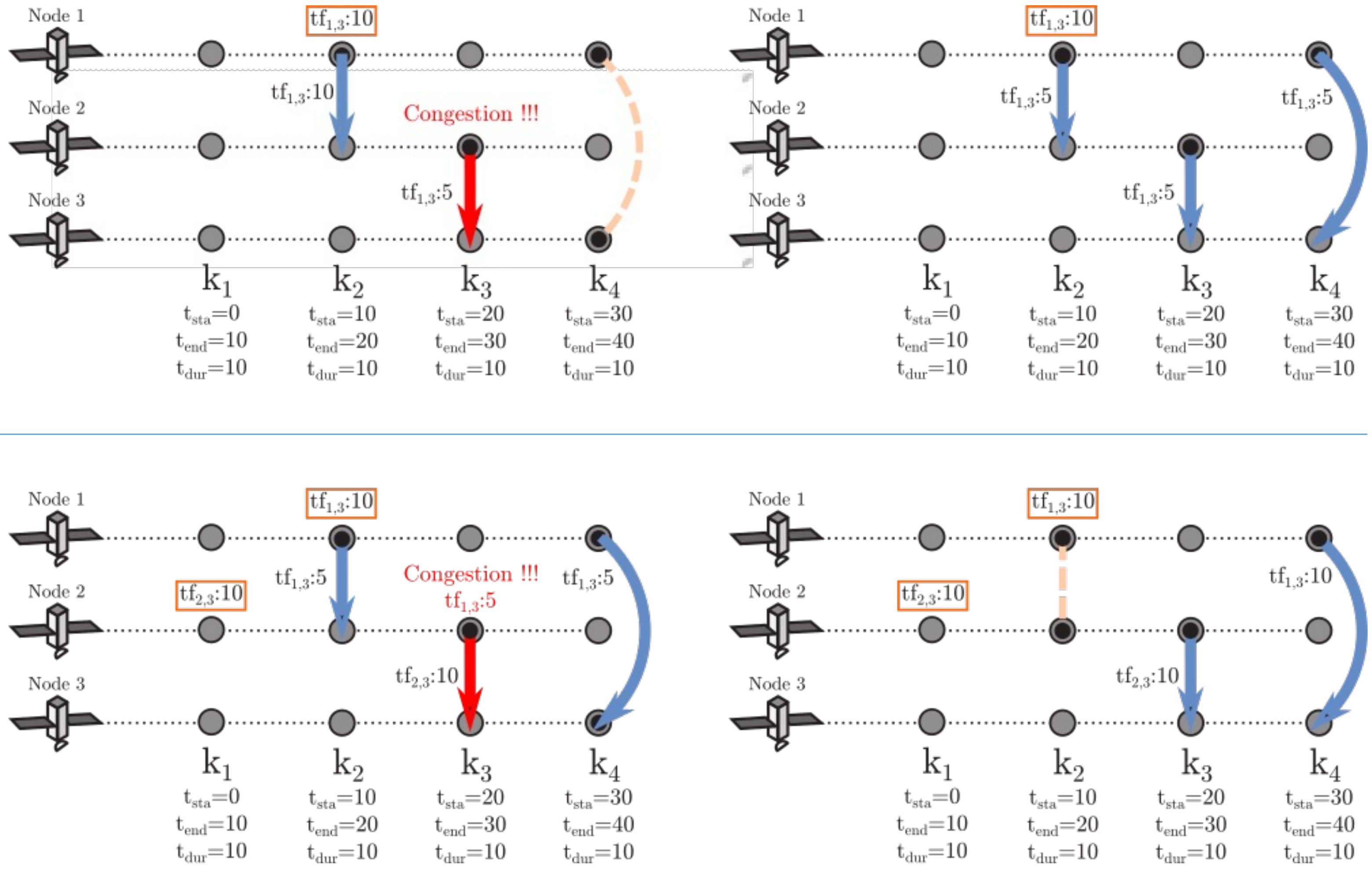
Candidate list created on a per-bundle basis
(uses bundle deadline and size)

[1] Fraire, Juan A., Olivier De Jonckère, and Scott C. Burleigh. "Routing in the space internet: A contact graph routing tutorial." Journal of Network and Computer Applications 174 (2021): 102884.

Modeling

Congestion

- *Reactive*
  - Custody transfer
  - Forecast warning
- *Proactive*
  - **Topology** awareness
  - **Traffic** awareness
    - Contact Plan Slicing [1]
    - AI for traffic prediction

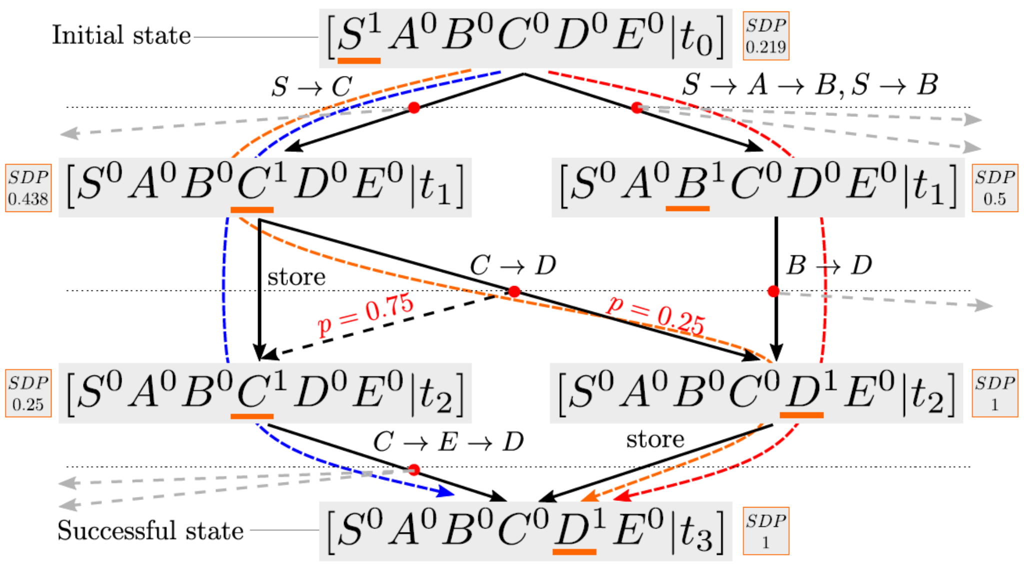


[1] Madoery, Pablo G., Juan A. Fraire, and Jorge M. Finochietto. "Congestion management techniques for DTN satellite networks." Int. Journal of Satellite Communications and Networking 36.2 (2018): 165-178.

Modeling

Uncertainties

- Contacts $\rightarrow$ associated probability
  - Multi-copy forwarding
  - Timing information available from the contact plan
    - Traditional probabilistic routing, such as S&W or PRoPHET work with a simplified timing model (frequency)
  - Markov Decision Process (MDP) can provide optimal policies [1]
    - Require efficient search heuristics [2]
    - And AI learning (e.g., Q-Learning) [3]



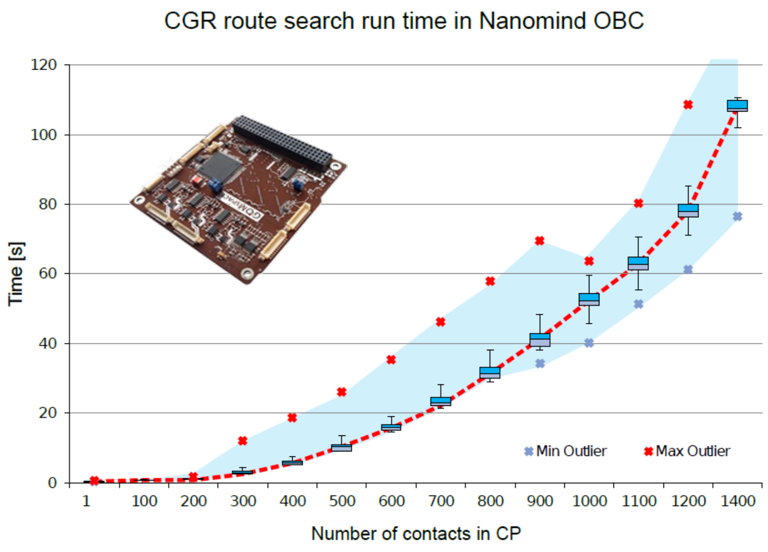
Markov Decision Process (MDP)

[1] Raverta, Fernando D., et al. "Routing in delay-tolerant networks under uncertain contact plans." Ad Hoc Networks 123 (2021): 102663.
[2] D'argenio, Pedro R., et al. "Comparing Statistical and Analytical Routing Approaches for DTN" Quantitative Evaluation of Systems: 19th International Conference, QEST 2022, Warsaw, Poland, September 12–16, 2022, Proceedings. Cham: Springer International Publishing, 2022
[3] D'argenio, Pedro R., et al." Comparing Statistical, Analytical, and Learning-Based Routing Approaches for DTNs" ACM Trans. on Modeling and Computer Simulation (TOMACS) (under review)

Modeling

Scalability

- Route computation effort scales with contact plan **size** and **duration**



CGR implementation in a CubeSat OBC [1]

Alternatives

- Operate with *centralized* routing [2]
- Algorithm *optimization*
  - Spanning tree over multi-graphs (SPSN) [3]
- Topology *splitting*
  - Inter-Regional Routing (IRR) [4]
- Learning *models*
  - Graph Neural Networks (GNN) [5]
    - Goal: reduce on-board computing effort

[1] Vega, Blas F., and Juan A. Fraire. "Experimental Evaluation of On-Board Contact-Graph Routing Solutions for Future Nano-Satellite Constellations." (2020).
[2] Fraire, Juan A., and Elias L. Gasparini. "Centralized and decentralized routing solutions for present and future space information networks." IEEE Network 35.4 (2021): 110-117.
[3] De Jonckère, Olivier, and Juan A. Fraire. "A shortest-path tree approach for routing in space networks." China Communications 17.7 (2020): 52-66.
[4] Alesi, N. 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.
[5] M. Olmedo, Juan A. Fraire "Routing in Scalable Delay-Tolerant Space Networks with Graph Neural Networks" International Conference on Embedded Wireless Systems and Networks (EWSN), 2023

Modeling

Others

- Partial contact plan update (Rachel)
- AI for fragmentation determination (Rachel)

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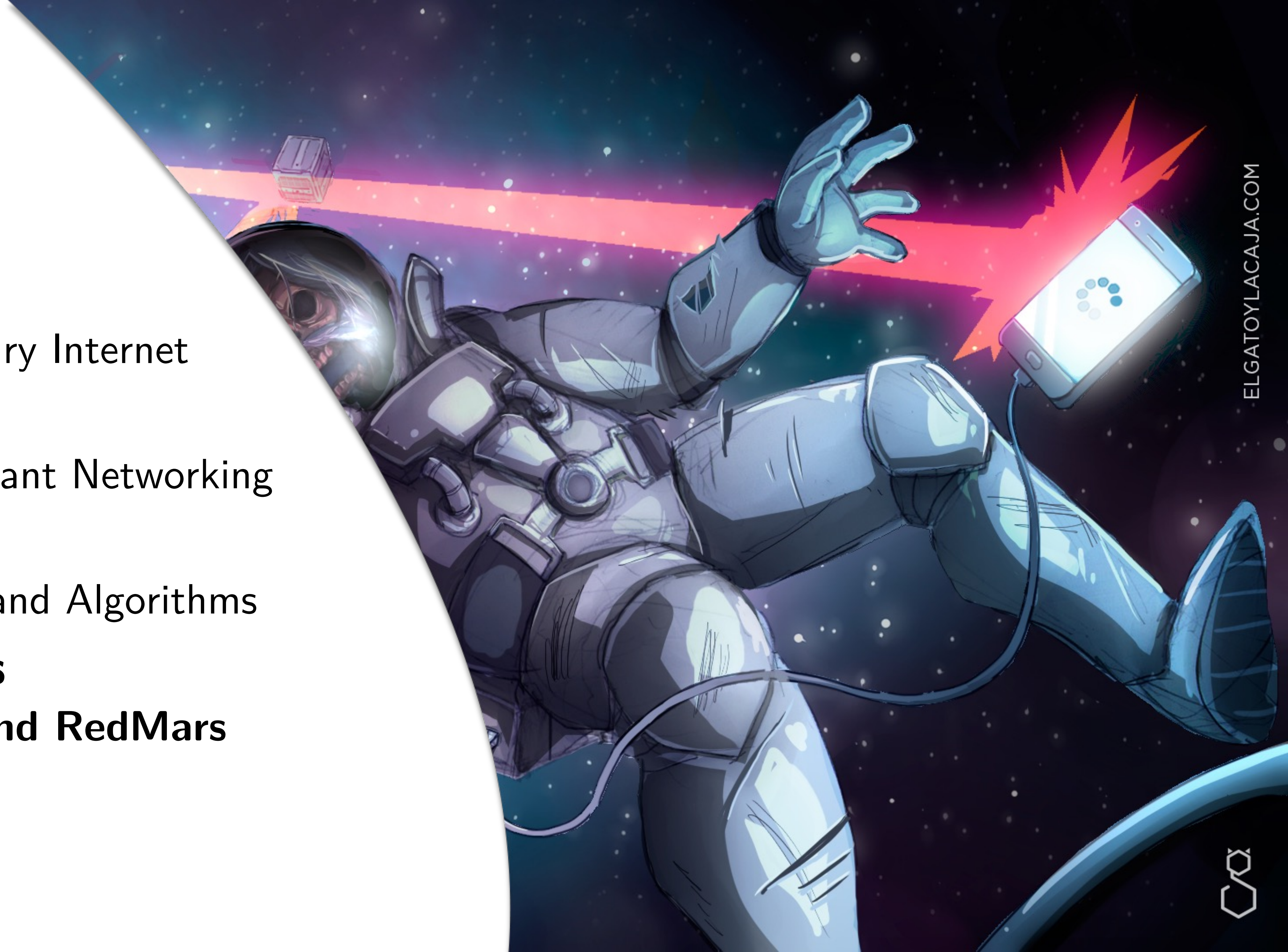
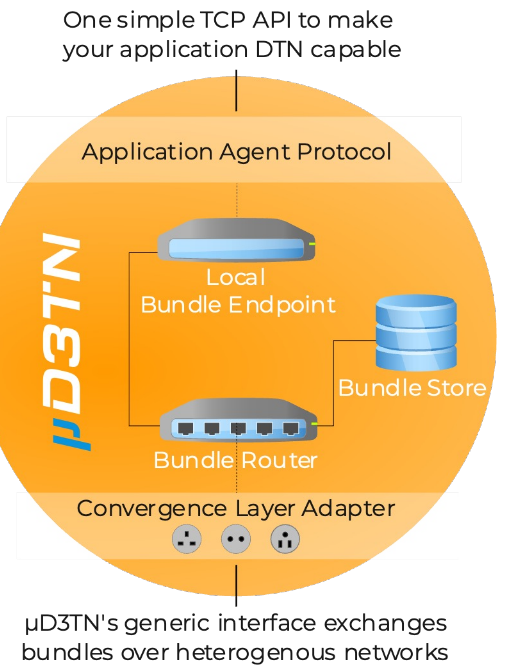
  - **ColdSun and RedMars**



Experiments

D3TN

- D3TN: Company located in Dresden and Miami
- Specialized in networking in *challenged environments*
  - Vehicular, underwater, and space
- Developer of µD3TN [1]
  - Open-source, lightweight DTN implementation
  - POSIX/Linux and STM32 microcontrollers (FreeRTOS)
  - First space-tested BPv7 implementation



COLDSUN ops-sat REDMARS → esa, Federal Ministry of Education and Research

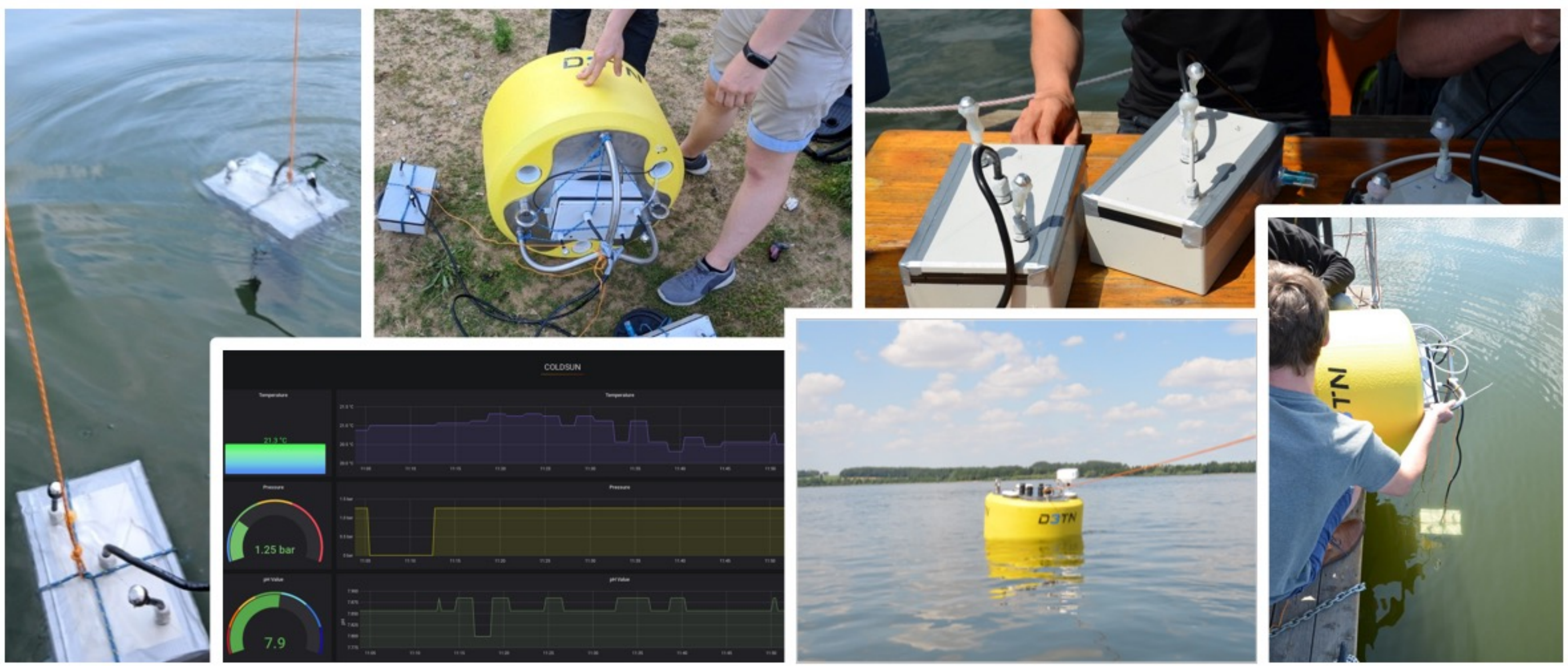
[1] https://d3tn.com/ud3tn.html - uD3TN features

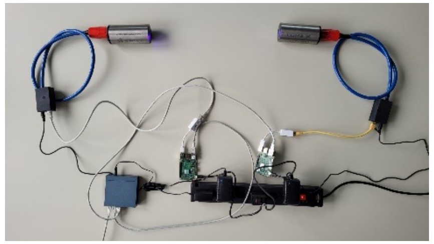
- **Northbound**: Straightforward application integration thanks to socket-based (TCP or Unix domain socket) Application Agent Protocol (AAP) interface
- **Core**: Full compatibility with ipn and dtn EID schemes, neighbor discovery (IPND), Bundle-in-Bundle Encapsulation (BIBE), modular opportunistic-deterministic DTN routing, and BPSec
- **Southbound**: Supports several Convergence Layer Adapters (CLA) such as CCSDS SPP, MTCP (draft v0), TCPCLv3 (RFC 7242), and TCPCLv4 (*)

Experiments

ColdSun

- *Underwater* to *Buoy* to *Satellite* to the *Internet*
  - End-to-end data transport with µD3TN ORBCOMM





Acoustic modems

Optical modems

Satellite link

Off-shore buoy with space and underwater interfaces

Underwater link

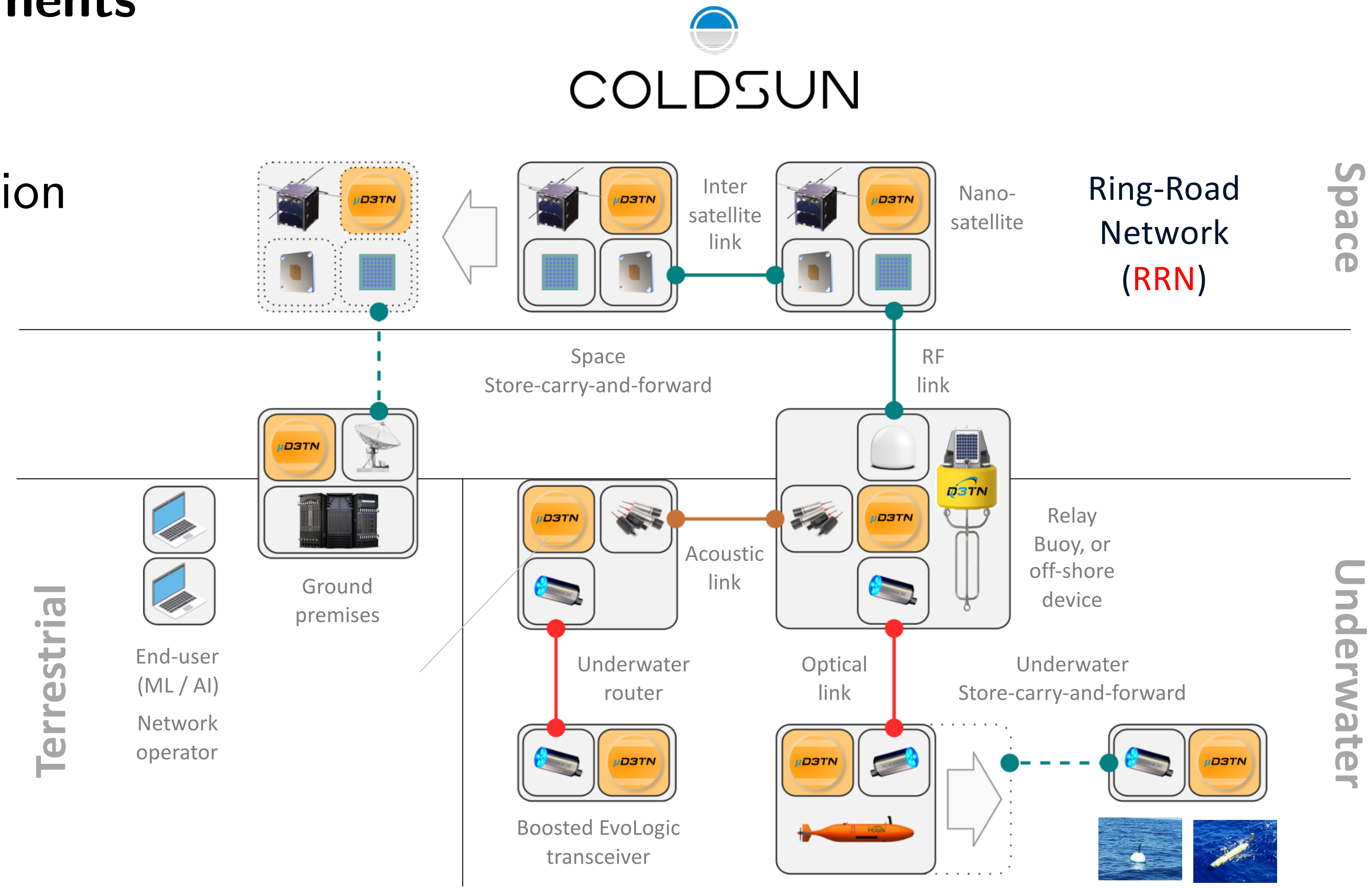
AUV for dynamic data collection (data mule: higher throughput than direct link)

esa business applications

Experiments

ColdSun

- Vision

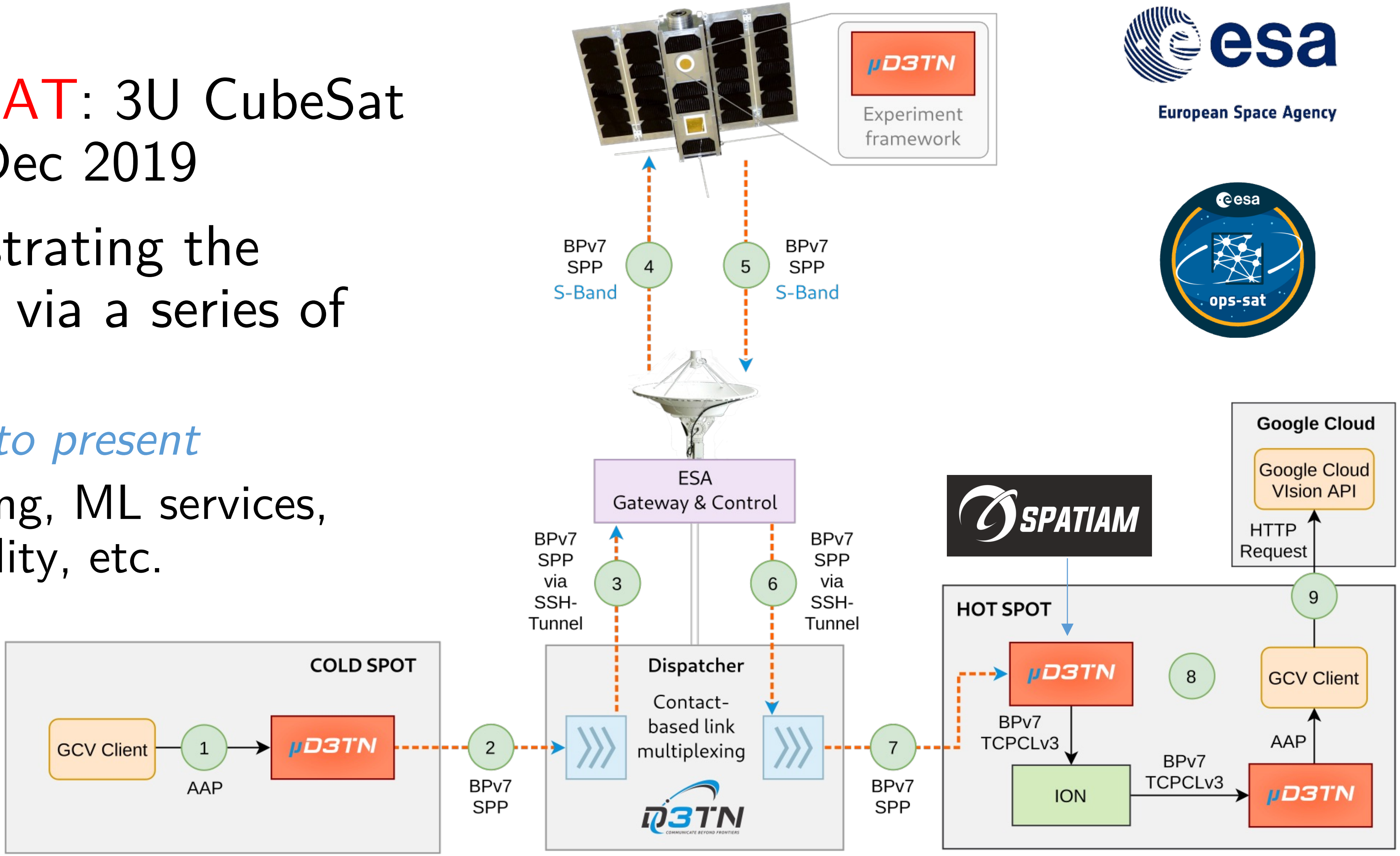


Experiments

OPS-SAT

- ESA's OPS-SAT: 3U CubeSat launched in Dec 2019
- Goal: demonstrating the RRN concept via a series of experiments
  - *From 2020 to present*
  - Web browsing, ML services, interoperability, etc.

µD3TN on the ground and in space

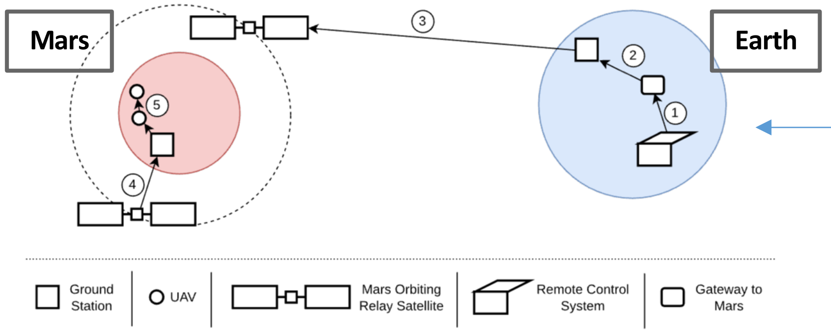


Experiments

RedMars

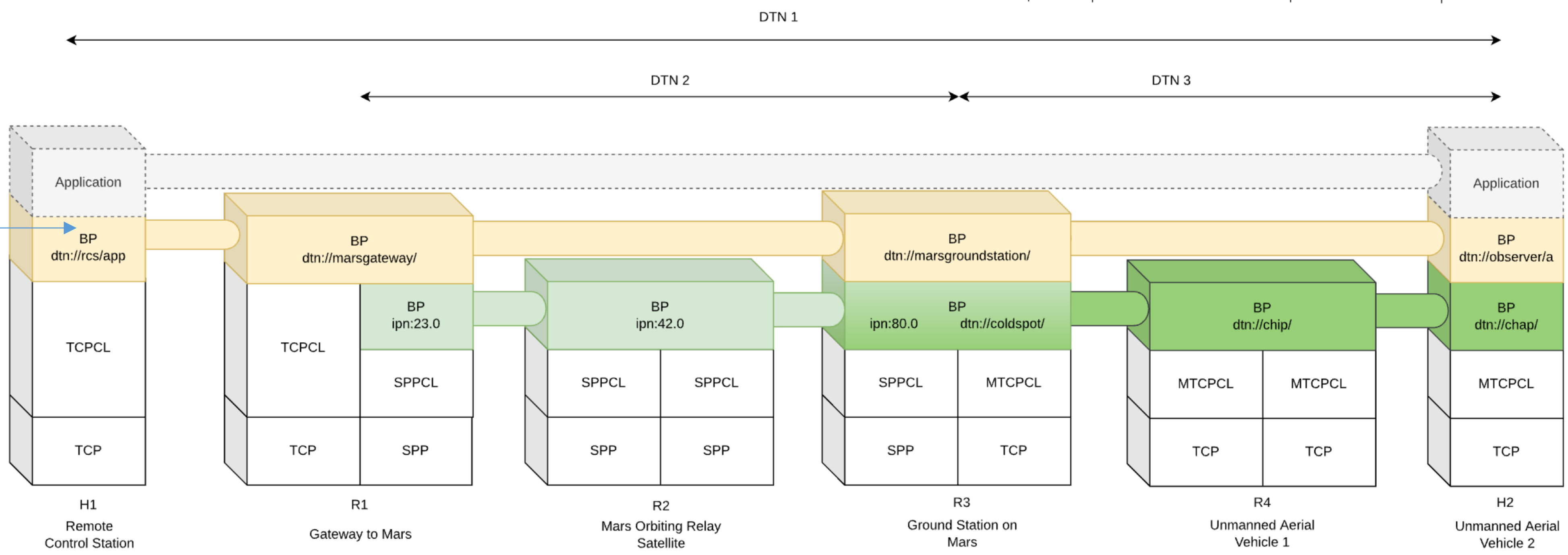
REDMARS

- Adapt Recursive Inter-Network Architecture (RINA) [1] into DTN
  - Node mobility, function recursivity, etc.



Scenario: Drone(s) data transport in Mars via DTN

BIBE to achieve network scopes

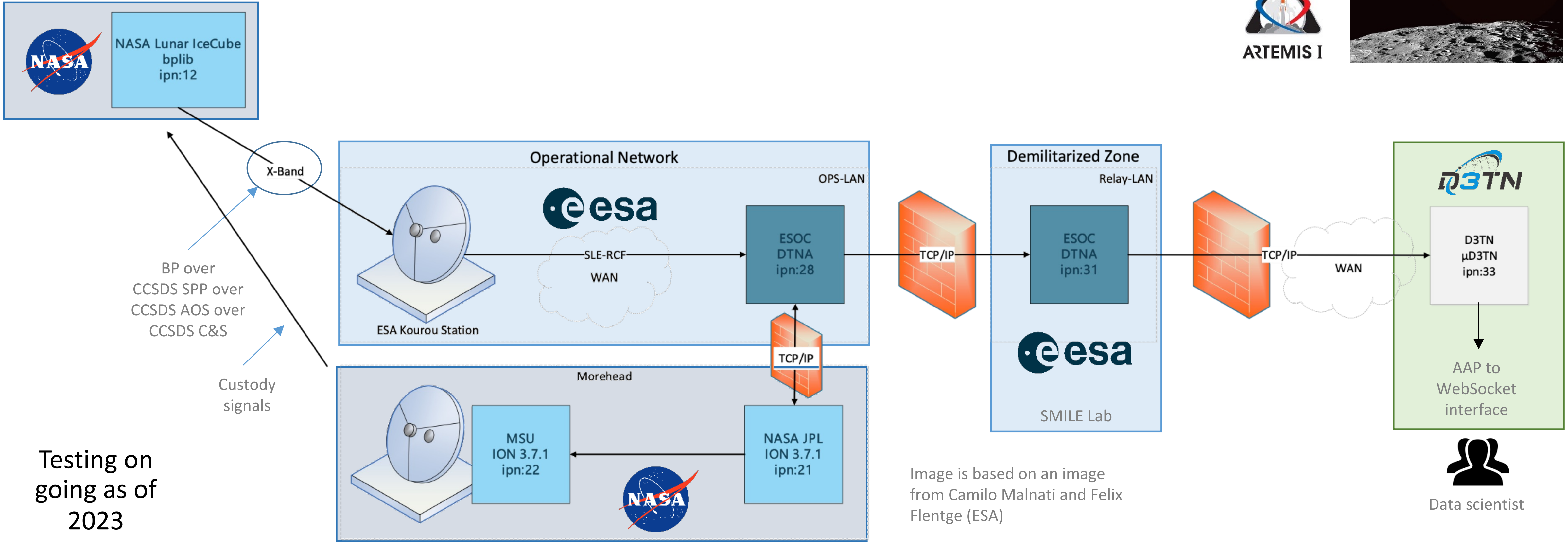


[1] Day, John. Patterns in network architecture. Pearson Education India, 2007.

Experiments

RedMars

- Lunar IceCube [1] cross-agency data exchange via DTN



Testing on going as of 2023

Image is based on an image from Camilo Malnati and Felix Flentge (ESA)

[1] https://en.wikipedia.org/wiki/Lunar_IceCube

Takeaways

Thanks for listening!

- **DTN brings time into the loop**
  - Adds a new dimension → asks for new modeling and experimental approaches
- **Modeling**
  - Data structures and algorithms are available, but flexibility/scalability are limited → Plenty of improvement and research opportunities ahead
- **Experimentation**
  - Stacks exist, but the reduced application scope hinders large-scale/long-term validation → Developing for terrestrial contexts might be the way
- **Artificial Intelligence**
  - Sometimes forced in networks where data is predictable and readily available
  - The challenge rests more in efficiently using the data (we have time)

Delay-Tolerant Networking Modeling and Experimentation

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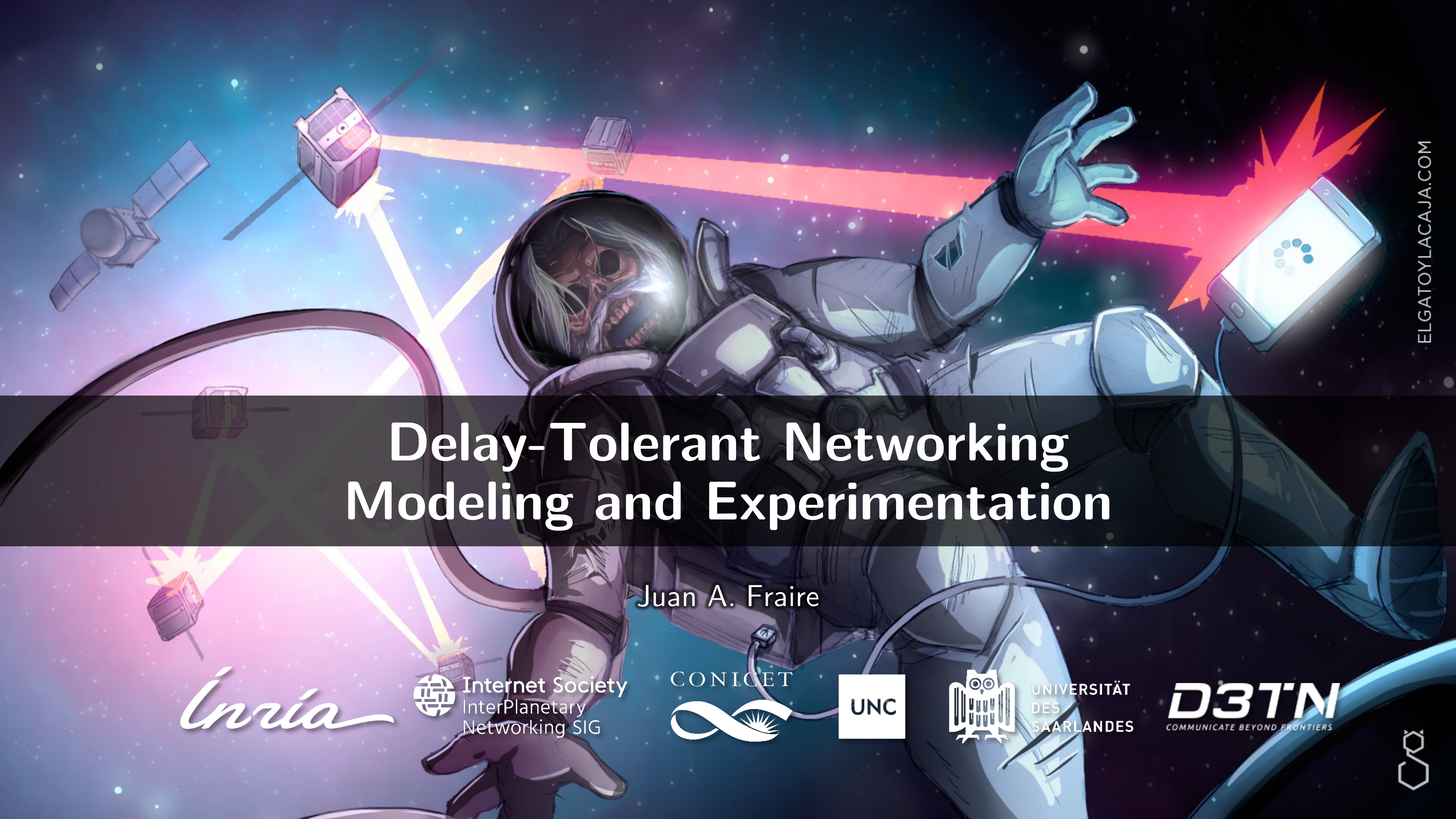

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