Transient Faults
in
Spaceborne Delay Tolerant Networks

Intrinsic Robustness
&
Smart Re-routing

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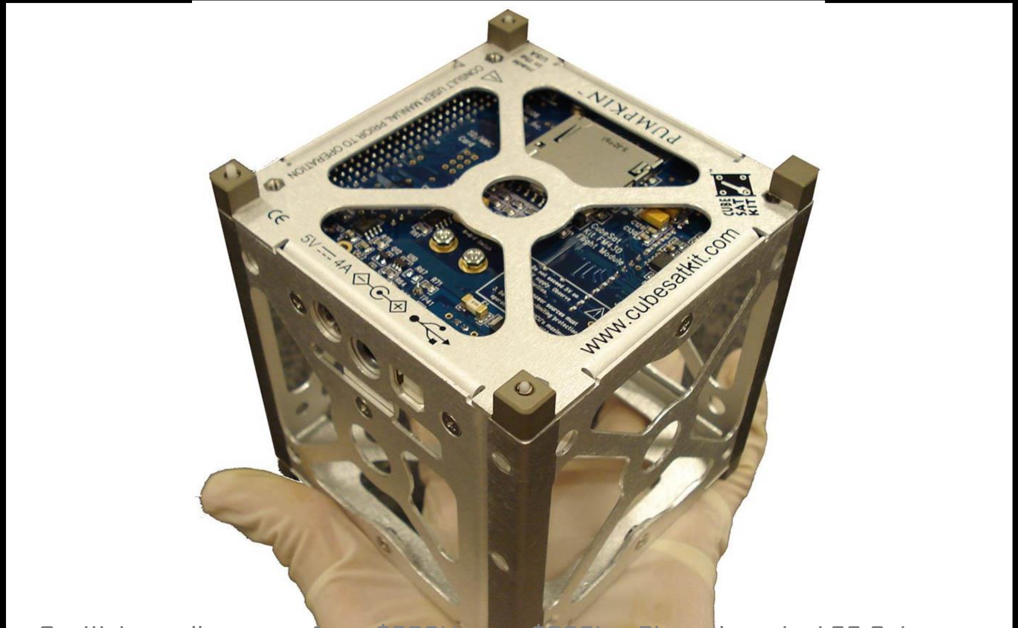
Agenda

- Context
- **Space Networking**
  - Continuous Networking
  - **Delay-Tolerant Networking**
    - Use Cases & Overview
- **Intrinsic Robustness**
- **Smart Re-routing**

Context

The so-called “New Space”

SpaceX reduced launch costs from ~$200M to ~$60M, and is targeting ~$5M – Real state elevator for space?



OneWeb satellite costs from $500M+ to < $500k – Planet launched 88 Cubesats

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- Massive ride-share launches
- Cheap dedicated launches

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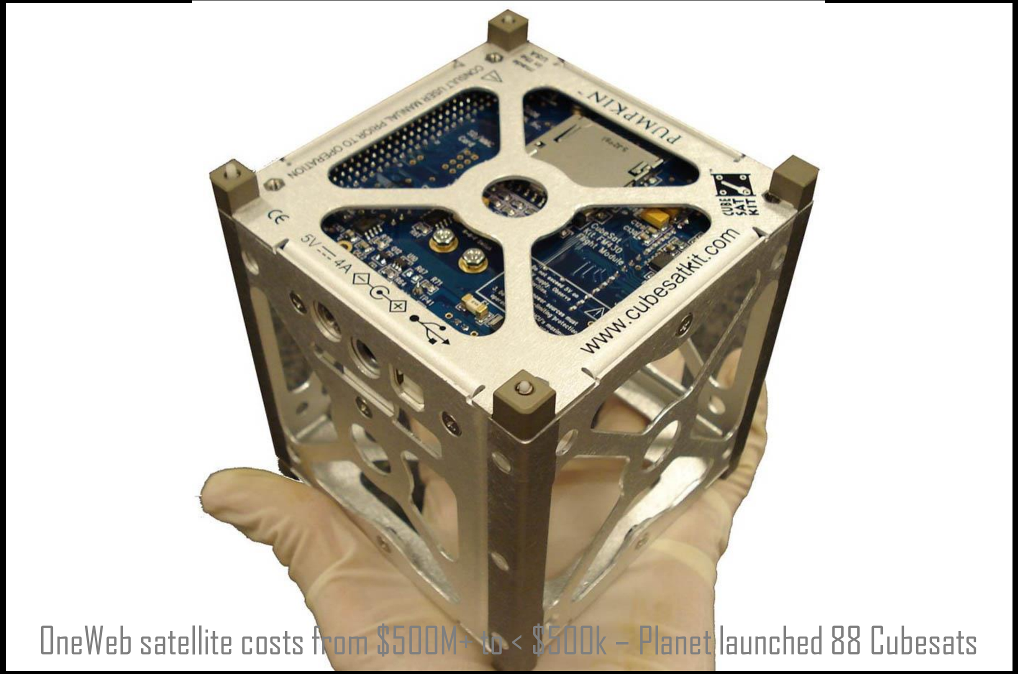

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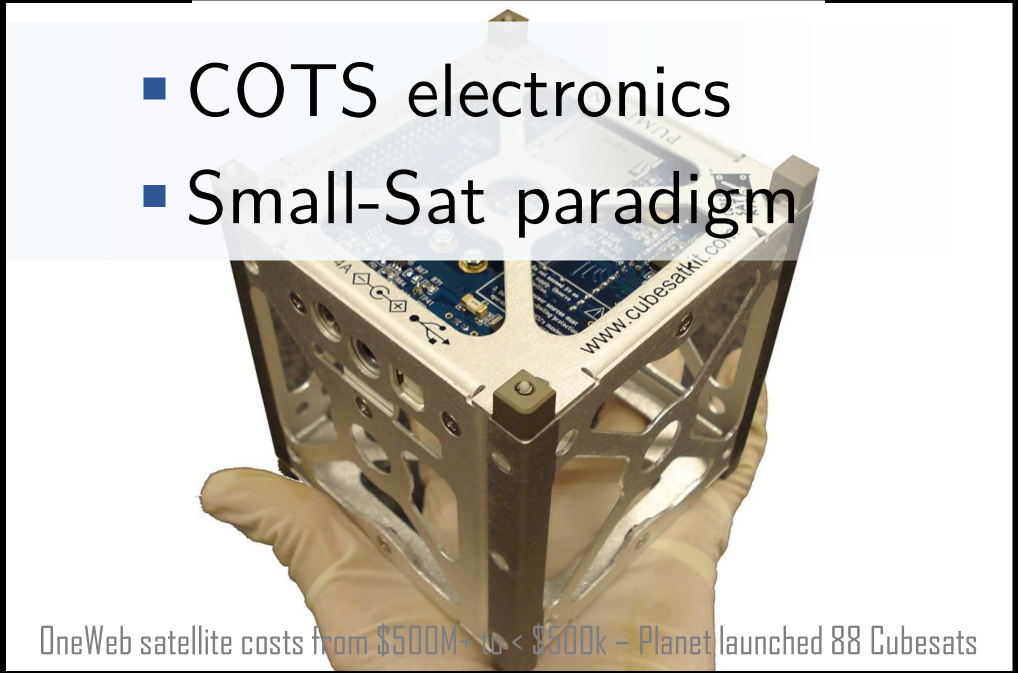

- COTS electronics
- Small-Sat paradigm

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OneWeb satellite costs from \$500M+ to < \$500k – Planet launched 88 Cubesats

- Global connectivity
  - **+\$150 bn** market
- Global imaging
  - **+\$50** bn market

Context

The so-called “New Space”

720 in Ka & Ku Band 1280 in V Band	OneWeb	BOEING	2,956 in Ka & V Band
4,425 in Ka & Ku Band 7500 in V Band	starlink	LEOSAT	108 Ka Band
3,263 in TBD	amazon	TelesatLEO	117 in Ka & V Band (Canada)
600 in Optical Band (India)	ASTROME	KEPLER	140 in Ku Band (Canada)
320 in TBD (China)	CASC	SAMSUNG	4,600 in TBD (South Korea)

+17,600 satellites by 2027

There are currently 5,000!

Context

The so-called "New Space"

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(Canada)

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Skepticism Interval

+17,600 satellites by 2027

There are currently 5,000!

Space Networking

Not Really Something New

- Let's plug them to the Internet and we are set! ☺
- Like some networks "successfully" did in the **past:**

inmarsat

13 GEO

Voice and **Internet**

iridium®

66+ LEO

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Space Networking

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Voice and **Internet**

Can TCP/IP succeed in all new space cases?

Space Networking

Nanosatellites Constellations for Earth Observation: The GOMX-4 Case

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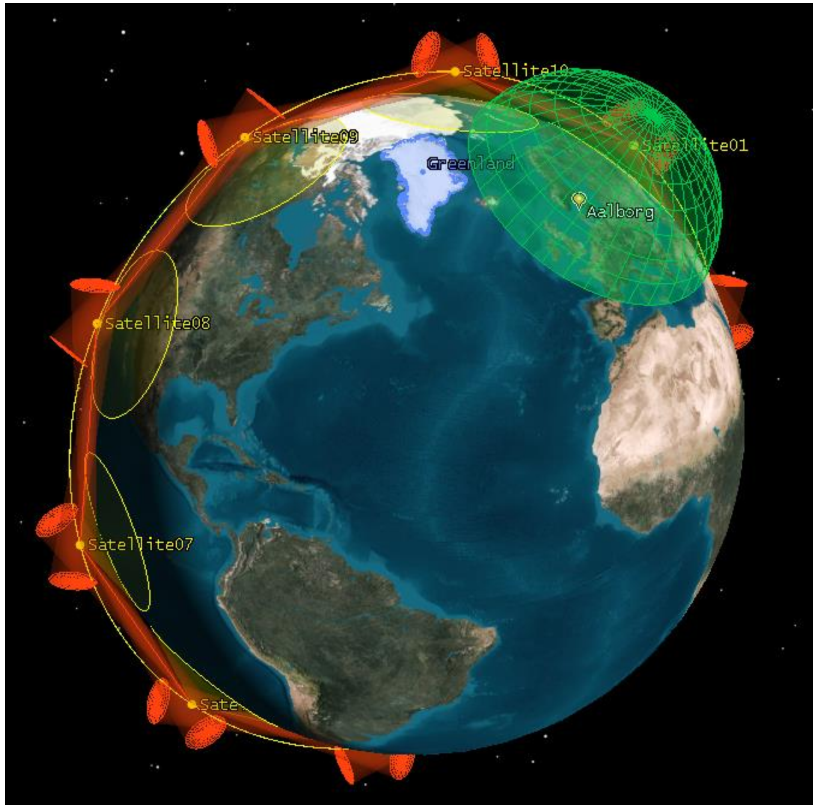
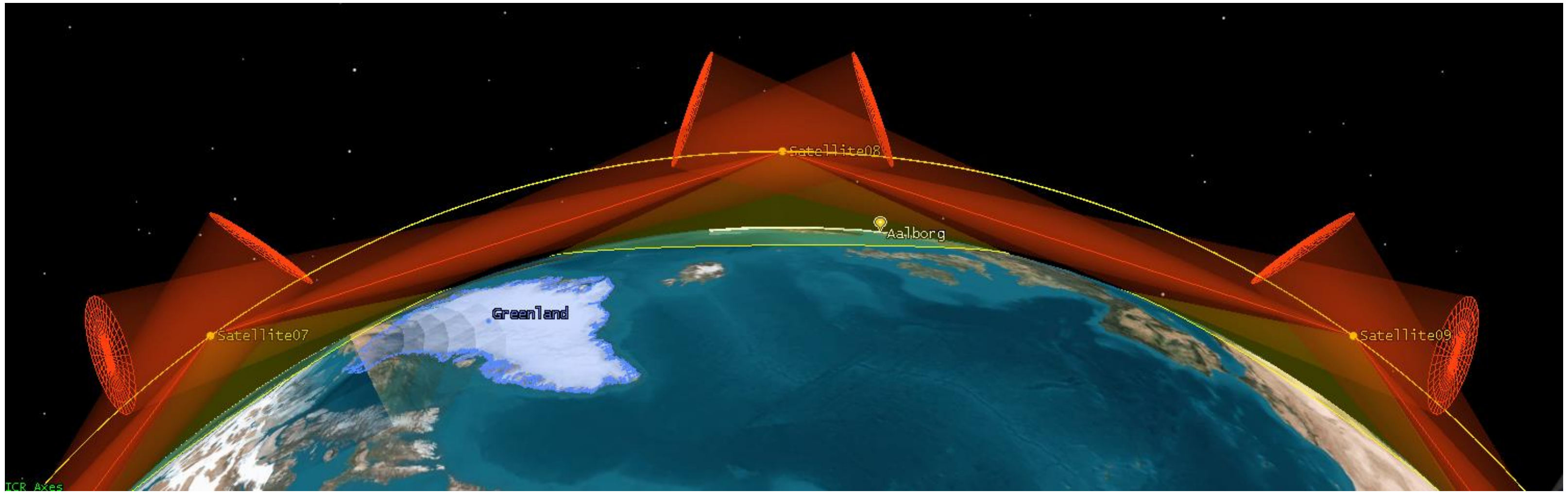
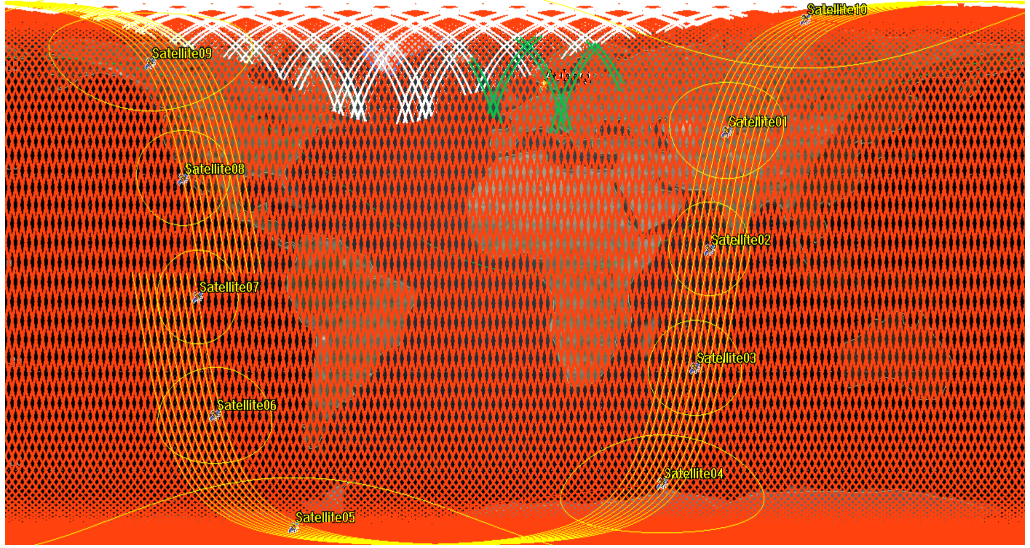
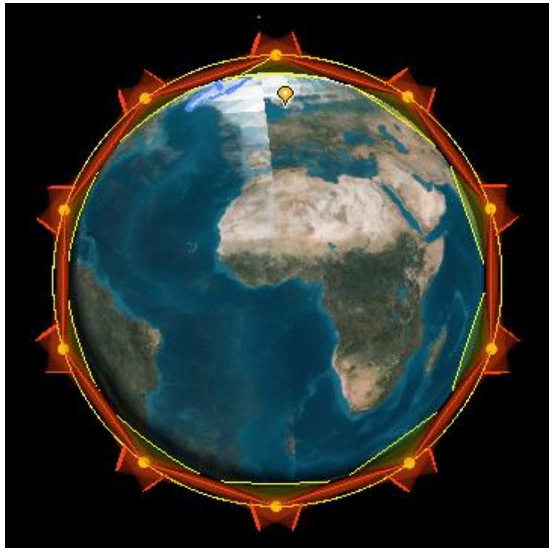
Space Networking

Nanosatellites Constellations for Earth Observation: The Ulloriaq Case









10 satellites in near-polar orbit provide almost constant visibility over Greenland and 2 contacts of ≈4 hs with Aalborg (Denmark)

Space Networking

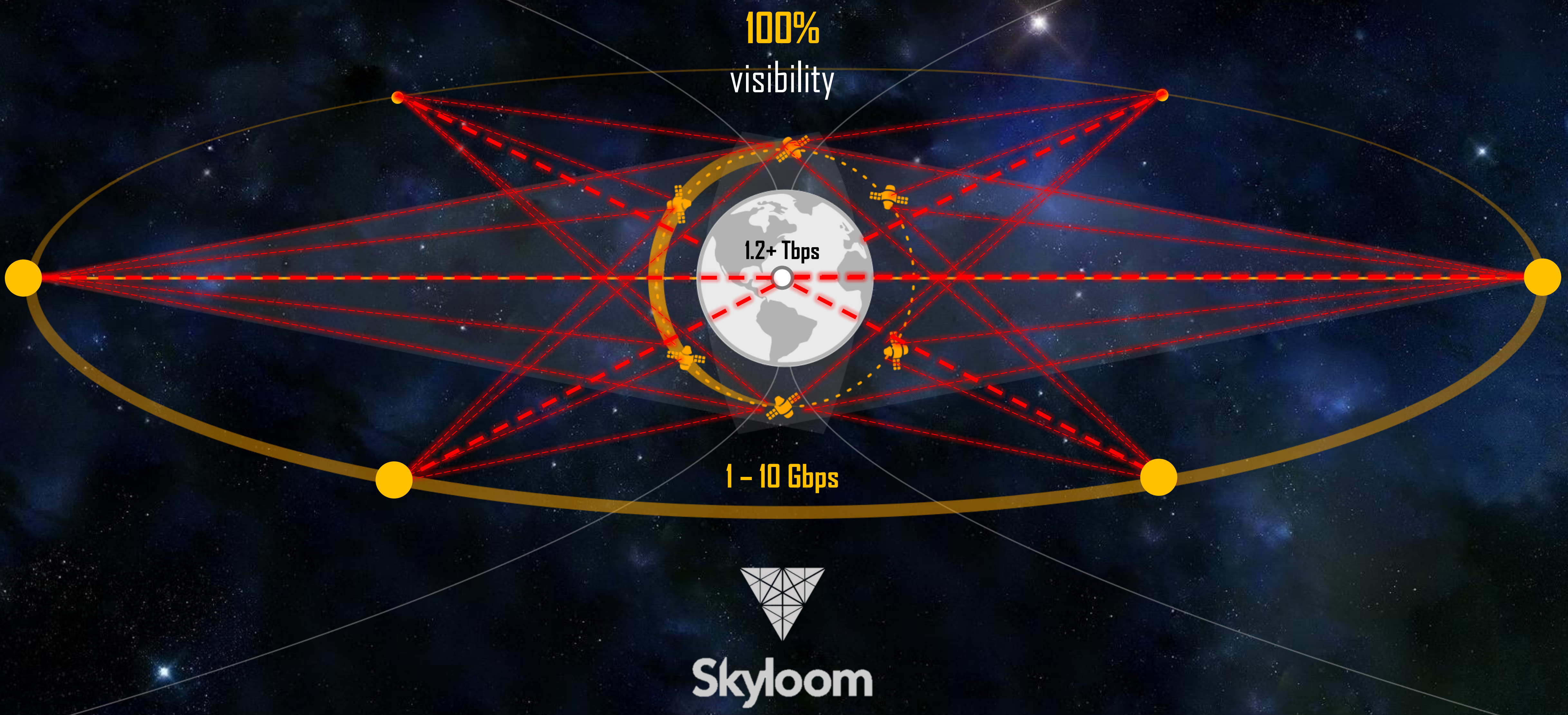
Nanosatellites Constellations for Data Relay: The Ring Road Case

Space Networking

Data Relay Backbone: The Skyloom Case

Space Networking

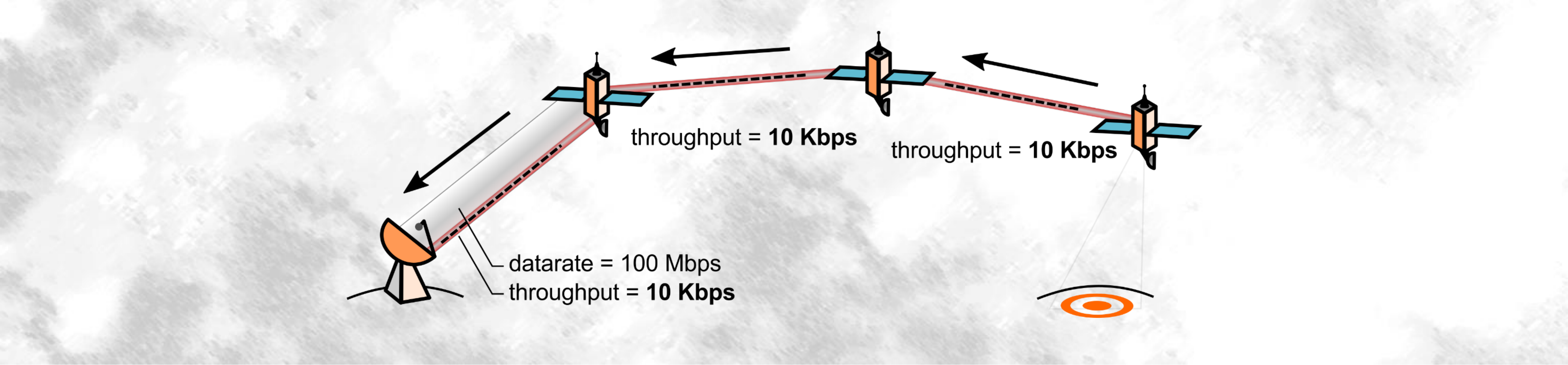
Data Relay Backbone: The Skyloom Case



Space Networking

Challenges

- Space networks challenged by:
  - **Occlusion** (orbital dynamics) — All
  - **Platform constraints** (limited interfaces) — Skyloom, Ulloriaq
  - **Power constraints** (sporadic link utilization) — GomX, Ulloriaq, C.Sun
  - **Heterogeneous data rates** (slow/long links) — Ulloriaq, Skyloom



Space Networking

Challenges - Approach 1)

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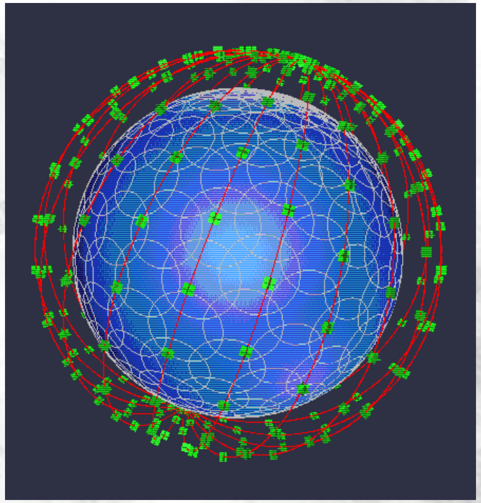
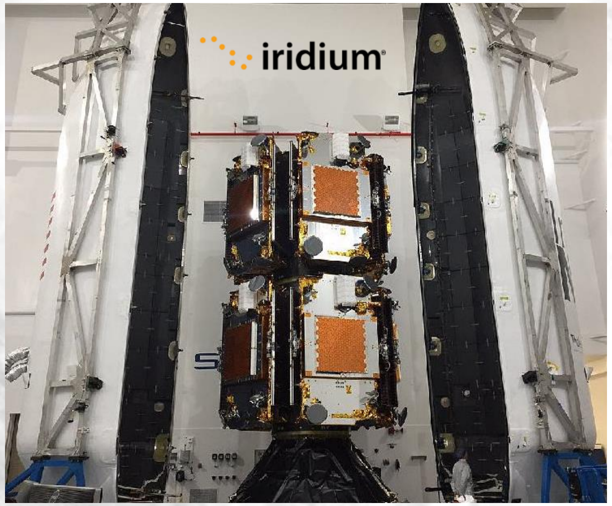

Iridium NEXT satellites: 4 ISLs, 860 kg, 3m x 2.5m x 1.5m – and – Falcon 9 rocket with Iridium and Starlink

Space Networking

Challenges - Approach 1)

- **1)** Internet Connectivity
  - Assumes
    - **Stable paths**
    - **Immediate** response
    - **Bidirectional** paths
    - **Low** error rates

  - Requires **extensive** infrastructure

Space Networking

Challenges - Approach 1) and Approach 2)

- **1)** Internet Connectivity
  - Assumes
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  - Requires **extensive** infrastructure

- **2)** Delay-Tolerant Connectivity
  - Assumes
    - **Unstable paths**
    - Long round trip times (**data storage**)
    - **Unidirectional** paths
    - **High** error rates
  - Requires **minimal** infrastructure

Space Networking

Challenges - Approach 1) and Approach 2)

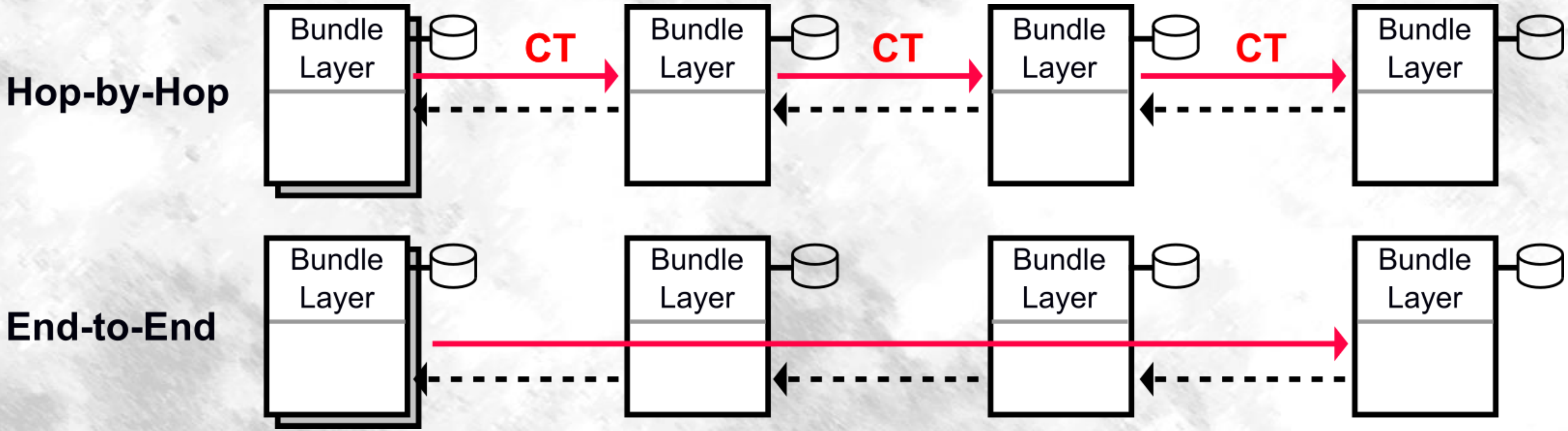
- **1)** Internet Connectivity
  - Assumes
    - **Stable paths**
    - **Immediate** response
    - **Bidirectional** paths
    - **Low** error rates
  - Requires **extensive** infrastructure
  - Voice/Video and Internet
    - Telephony
    - Real-time video
    - TCP/IP

- **2)** Delay-Tolerant Connectivity
  - Assumes
    - **Unstable paths**
    - Long round trip times (**data storage**)
    - **Unidirectional** paths
    - **High** error rates
  - Requires **minimal** infrastructure
  - Delay-tolerant data
    - IoT, observation (imaging/video) data
    - Personal messaging (email)
    - Telecommand and telemetry

Space Networking

Delay Tolerant Networks: Bundle Layer

- Overlay "bundle layer" that exists at a layer above other layers
  - Employs **persistent storage**, optional **end-to-end** and **hop-to-hop ack**



Space Networking

Delay Tolerant Networks: Specification, Implementations and Experiments

- Specifications by:
- Implementations: **ION** by NASA (JPL), **μPCN** by TUD, among others
- Flight experiments:
  - **Deep-space** (DINET mission)
  - **Cislunar** (LADEE mission)
  - **Near-Earth** (UK-DMC, permanently in the ISS, OPS-Sat & future missions)

Space Networking

Delay Tolerant Networks: Routing and Planning

- Connectivity expressed via **contacts**
- Predicted **contact plans** are exploited for **routing**

Space Networking

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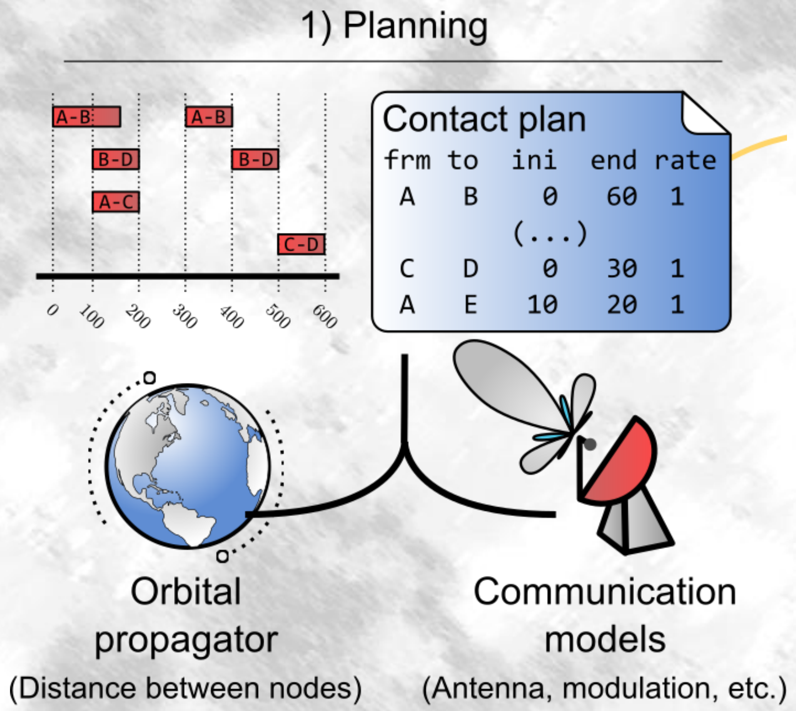

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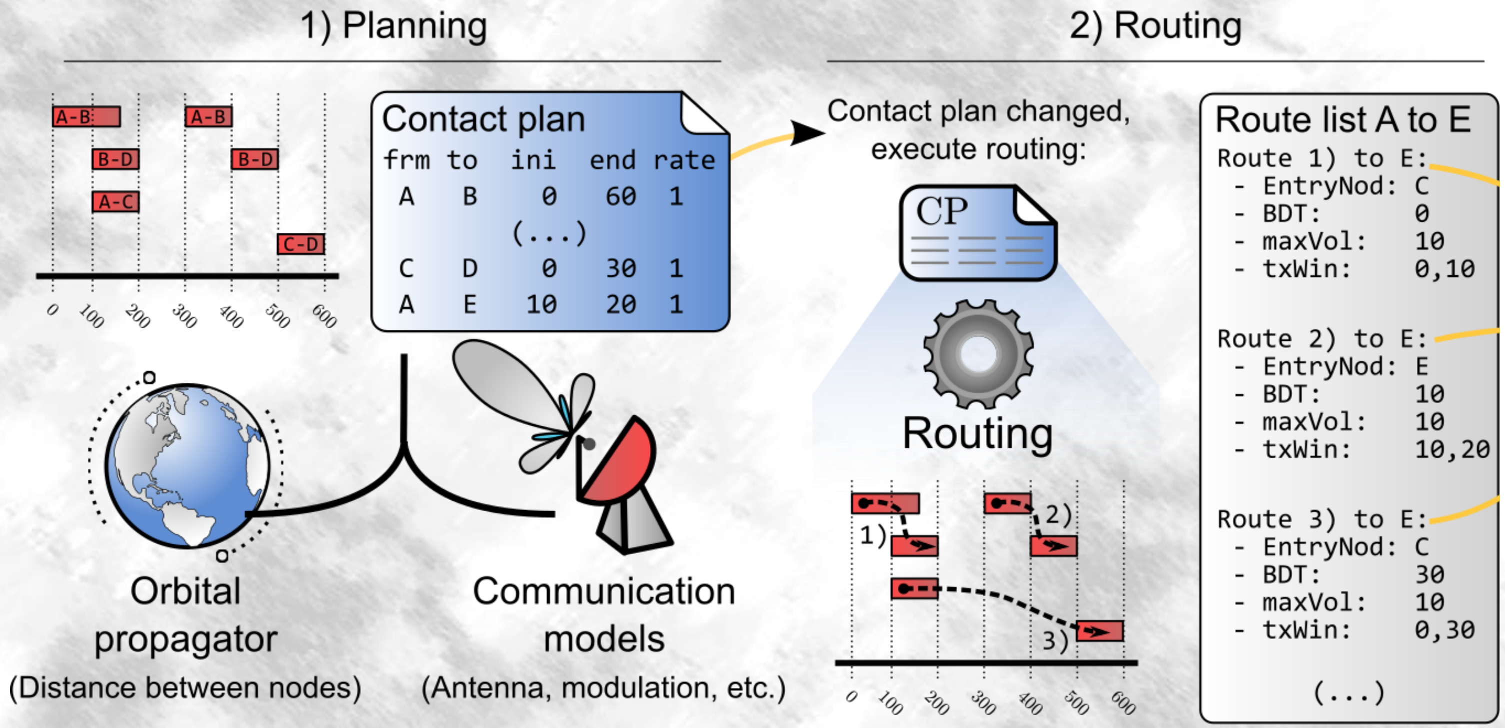

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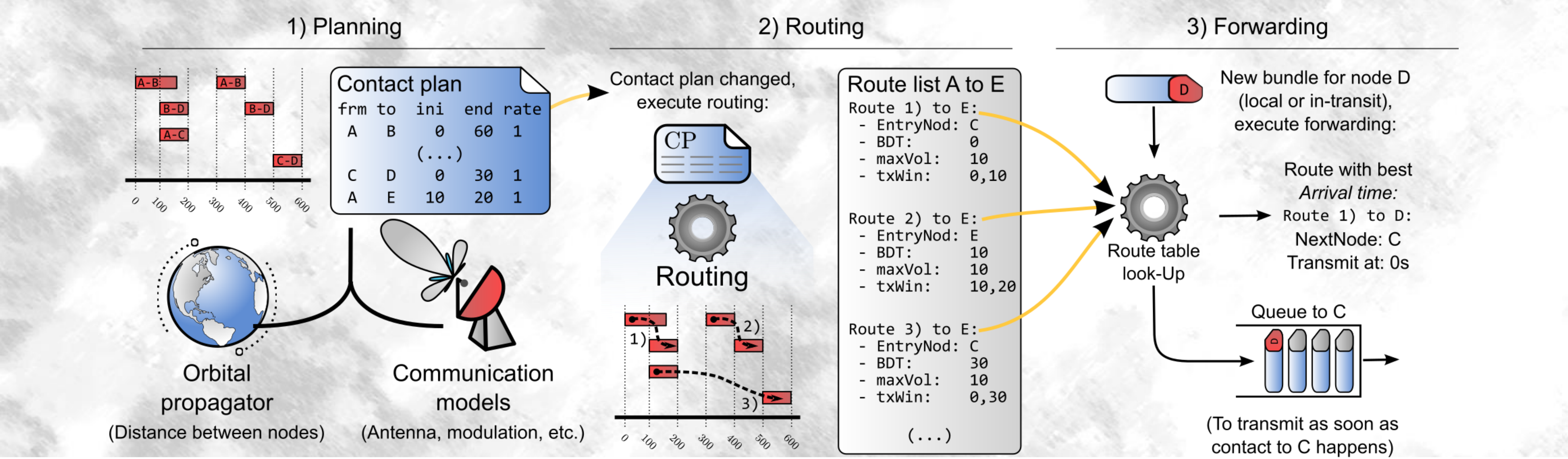

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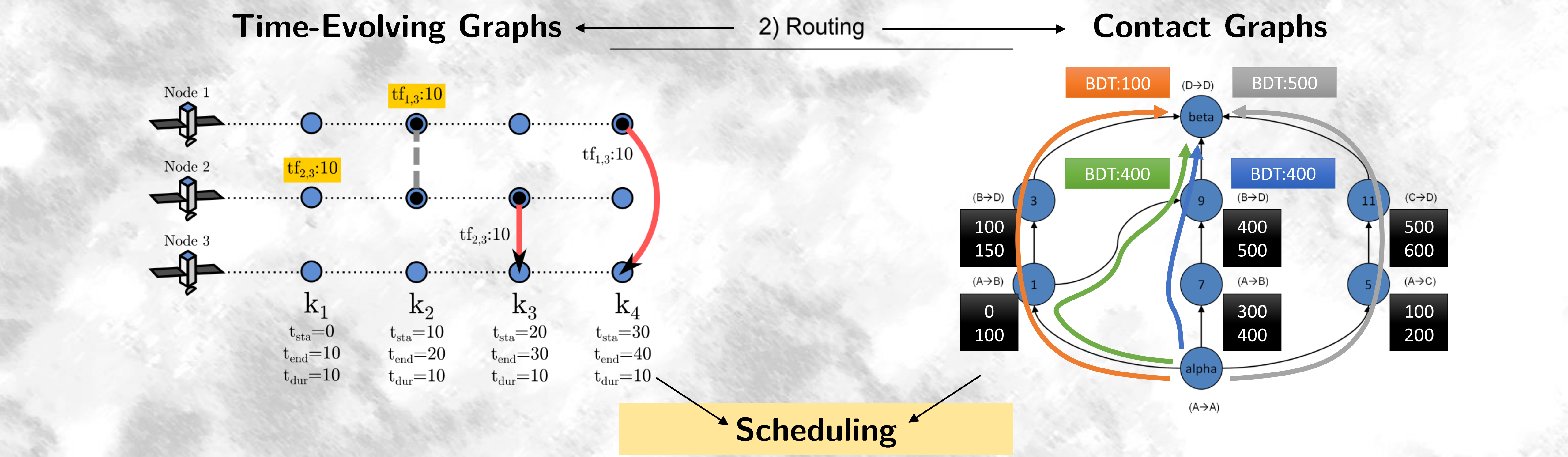


Space Environment

Plans might differ from reality

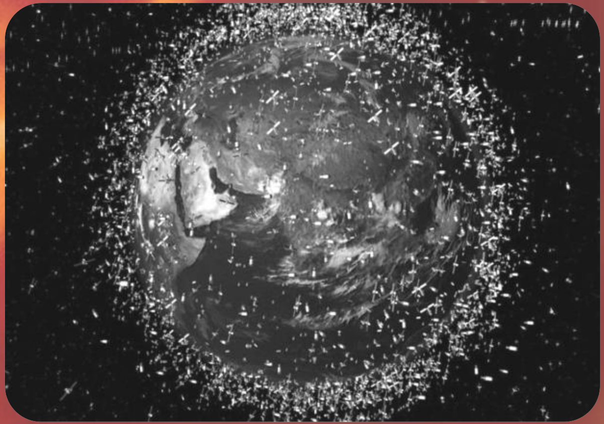
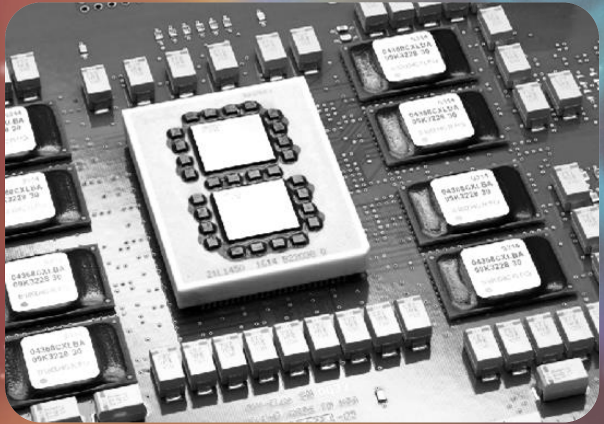
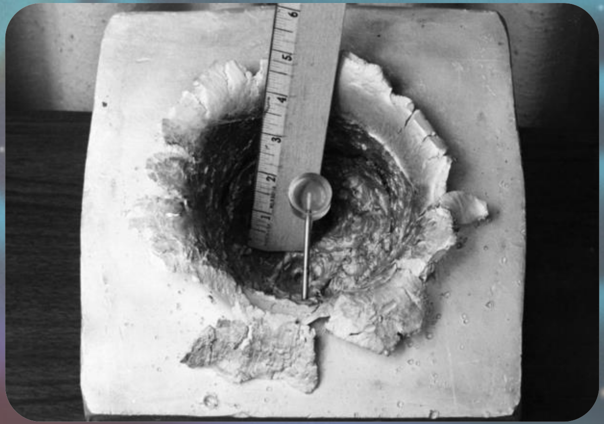
Launcher vibrations

Temperature cycles

Vacuum

Debris

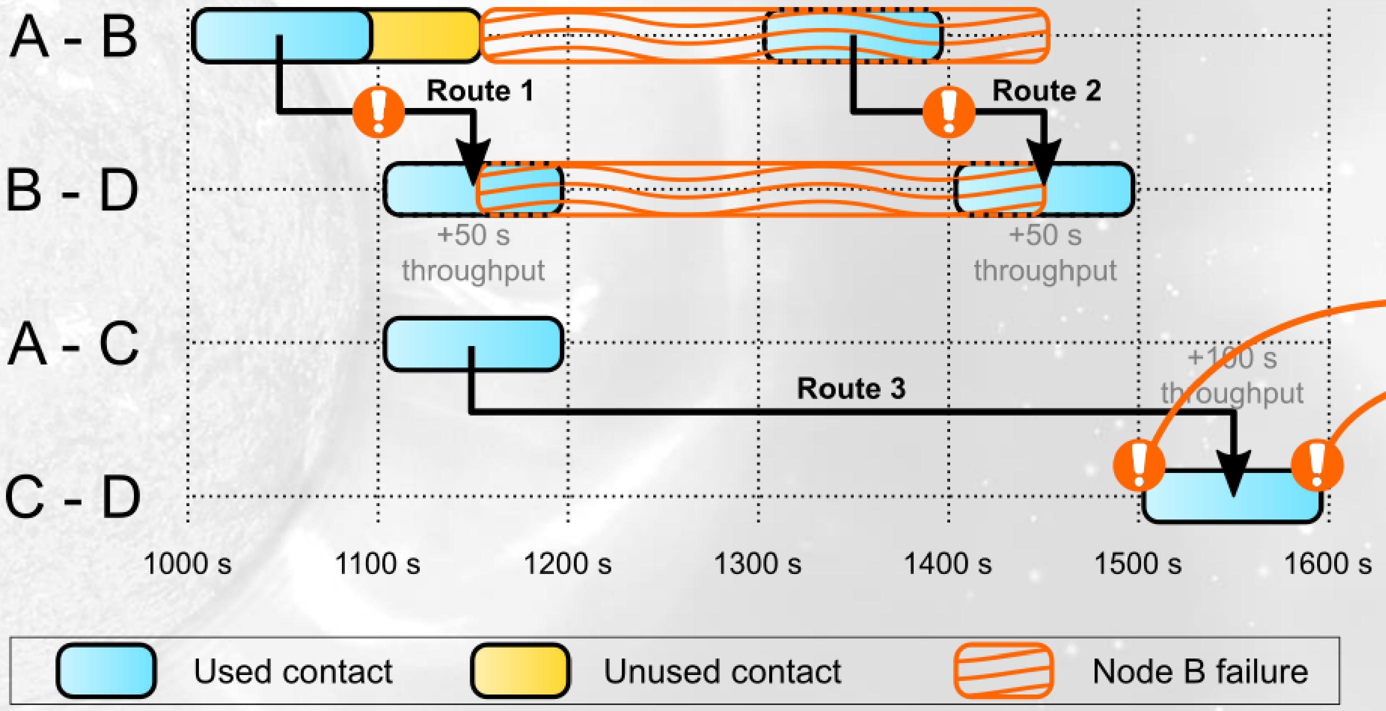
Radiation

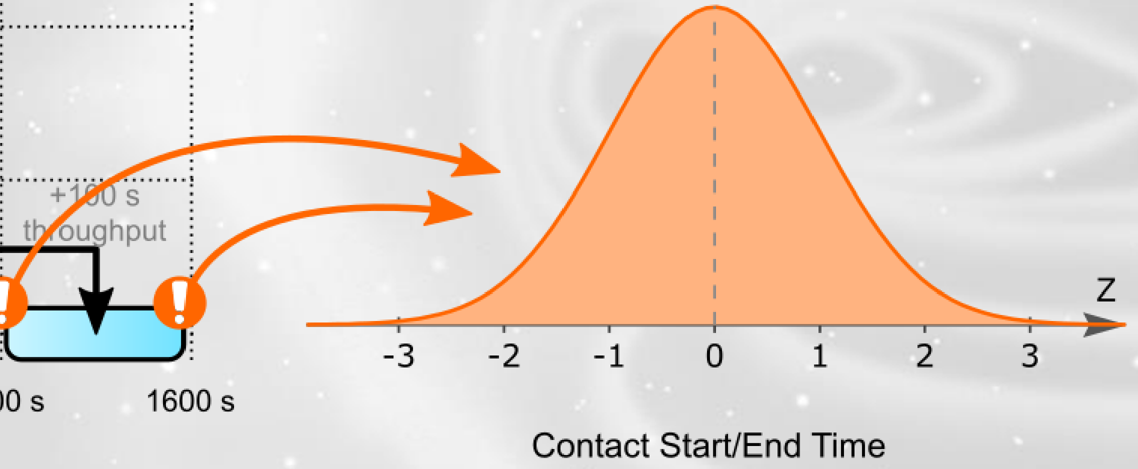





Space Environment

Plans might differ from reality

- Contact Plans can **fail** and be **inaccurate**





Intrinsic Robustness

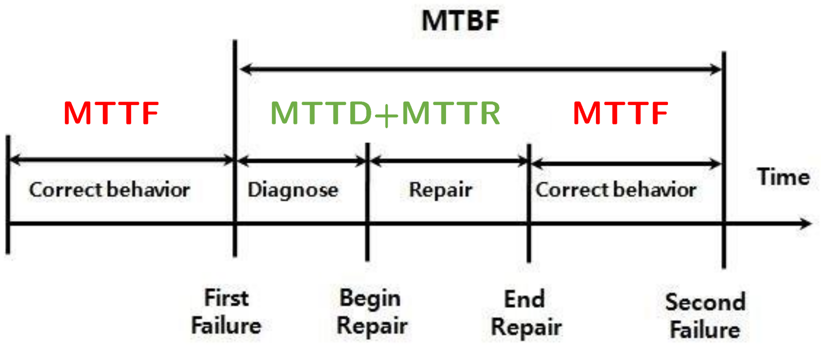
Exponential (Poisson) distribution

- Random **occurrence** in time and space of **transient failures**
- The probability of effectively **detecting and recovering**

$$F(t) = \int_0^t \lambda e^{-\lambda\tau} = 1 - e^{-\lambda\tau}$$

λ = Failure rate

1/ λ = **MTTF** and **MTTD+MTTR**



- Memoryless (no wear-out)

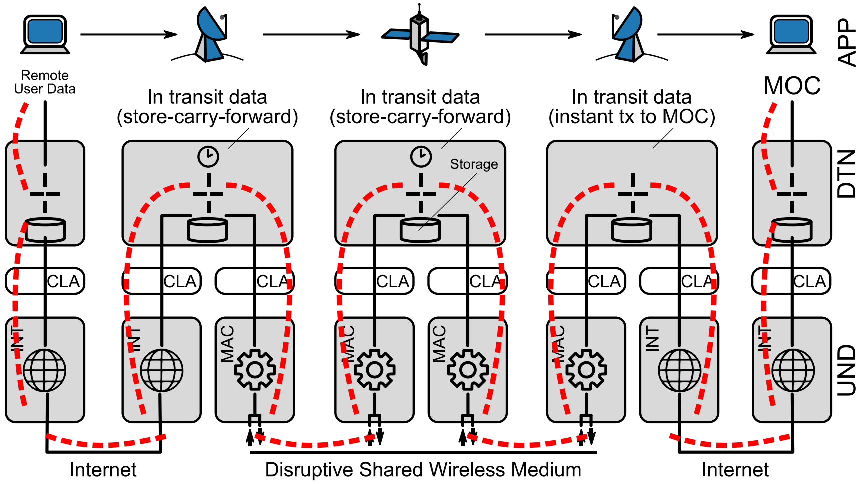
P. A. Ferreyra, C. A. Marques, R. T. Ferreyra and J. P. Gaspar, "Failure map functions and accelerated mean time to failure tests: new approaches for improving the reliability estimation in systems exposed to single event upsets," in *IEEE Transactions on Nuclear Science*, vol. 52, no. 1, pp. 494-500, Feb. 2005.

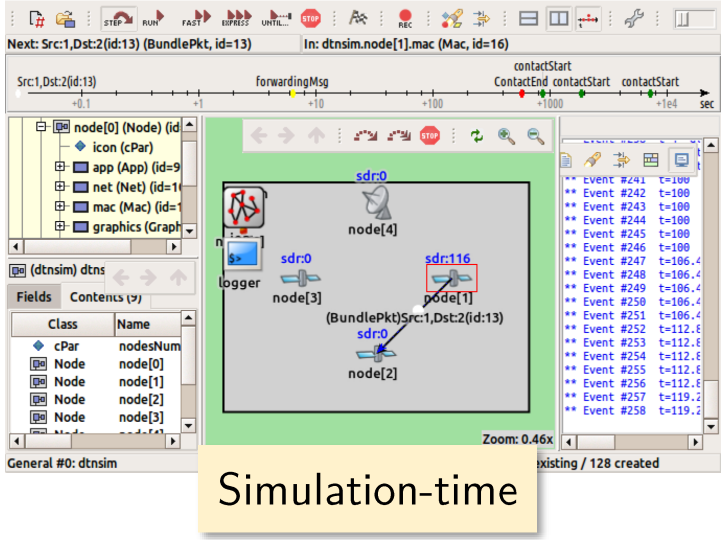
Intrinsic Robustness

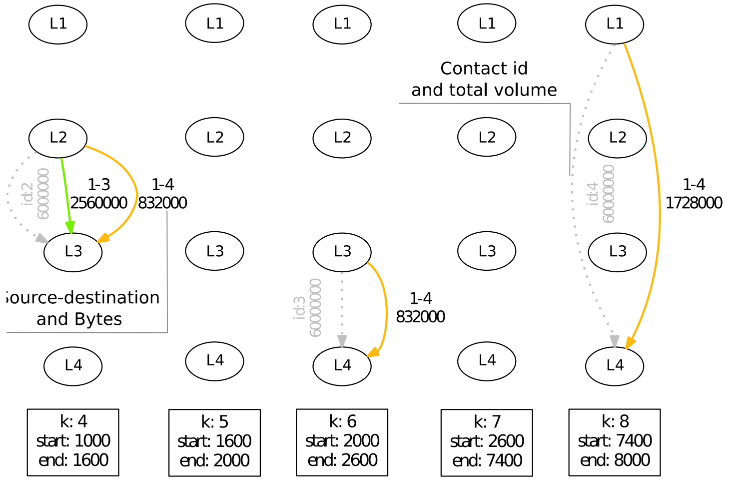
Tools and Methodology

- **DtnSim**
  - **Simulator: event-driven** based in Omnet++
  - **Emulator: real flight-code** (ION, μPCN) in the loop
  - Flexible and extendable fault module

Open source!







J. A. Fraire, P. Madoery, F. Raverta, J. M. Finochietto and R. Velazco, "DtnSim: Bridging the Gap between Simulation and Implementation of Space-Terrestrial DTNs," 2017 6th International Conference on Space Mission Challenges for Information Technology (SMC-IT), Alcala de Henares, 2017, pp. 120-123.

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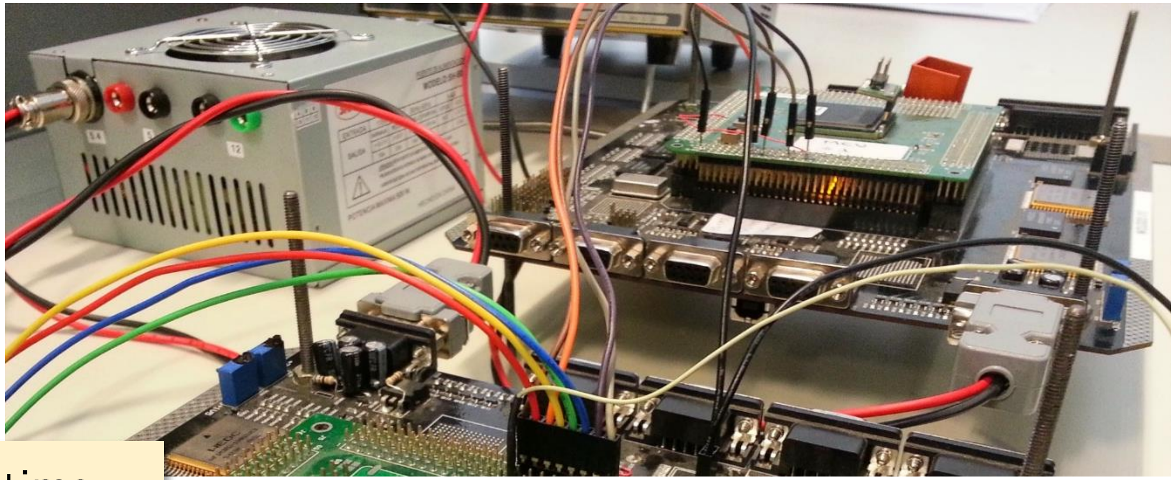
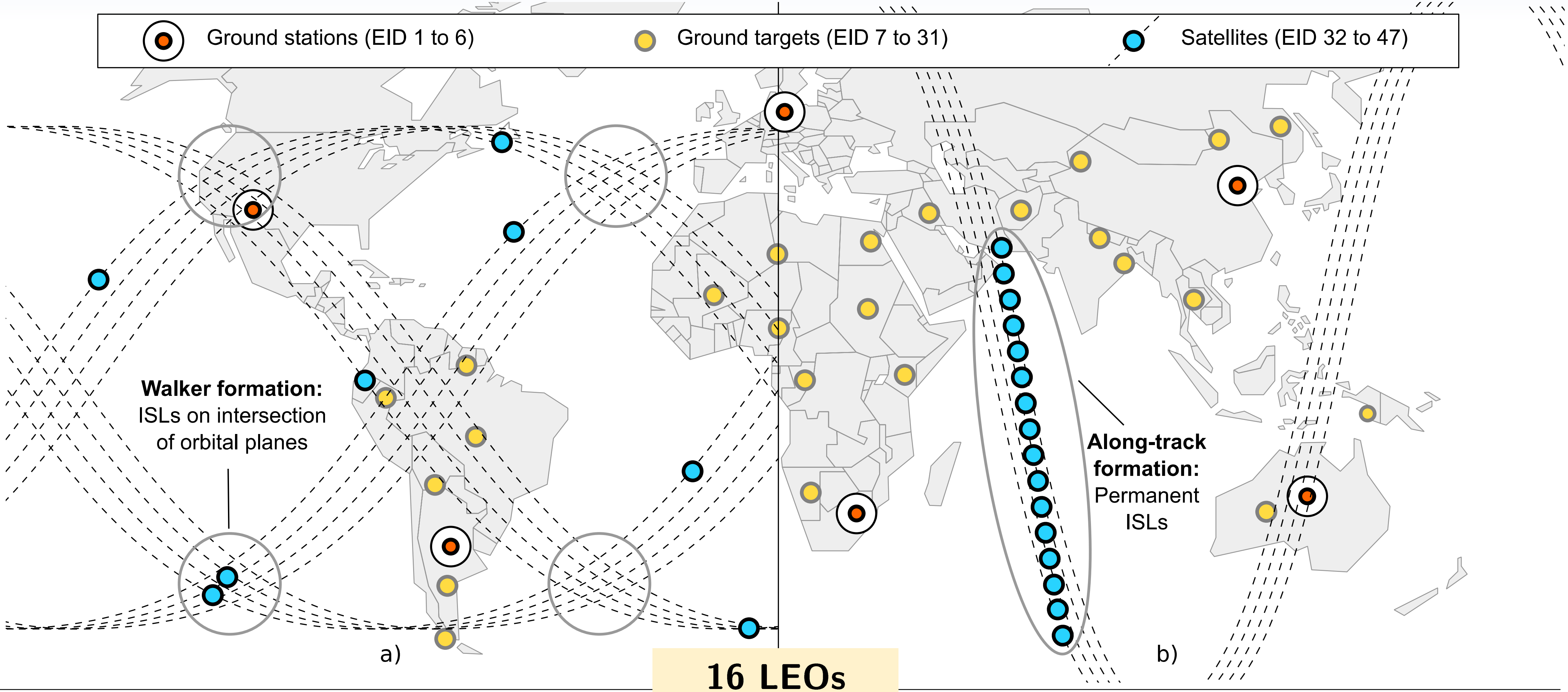


Real-time

J. A. Fraire, P. Madoery, F. Raverta, J. M. Finochietto and R. Velazco, "DtnSim: Bridging the Gap between Simulation and Implementation of Space-Terrestrial DTNs," 2017 6th International Conference on Space Mission Challenges for Information Technology (SMC-IT), Alcala de Henares, 2017, pp. 120-123.

Intrinsic Robustness

Scenario



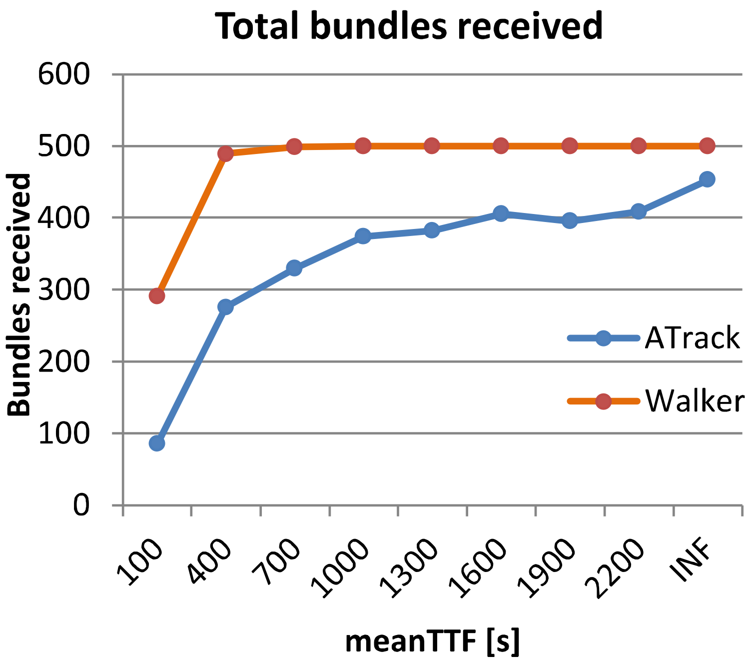
16 LEOs
6 GS
25 GT

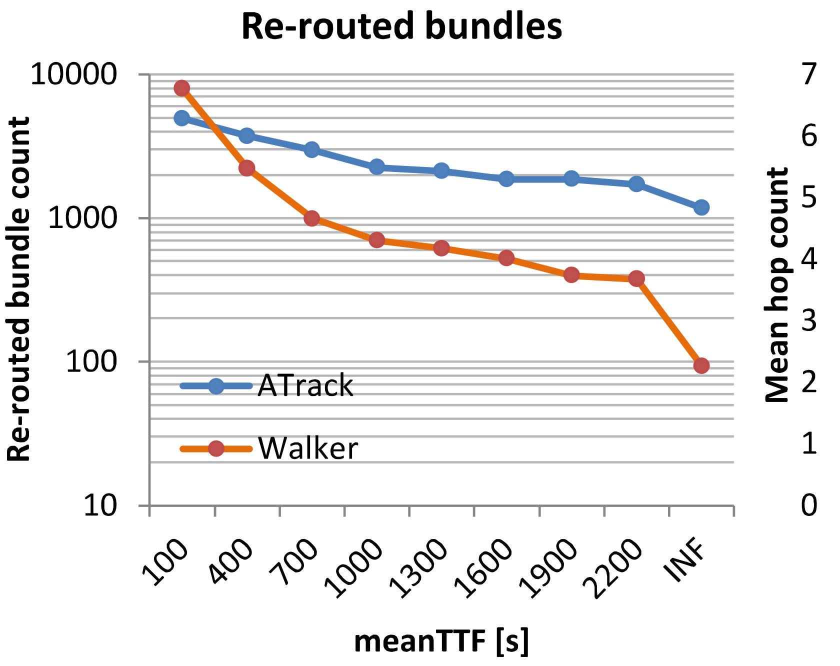
Walker Constellation | Along-Track Constellation

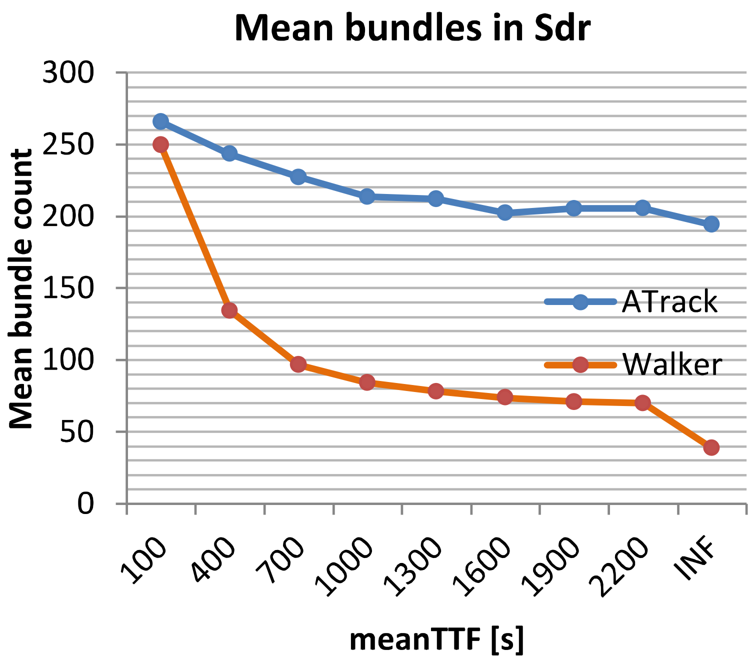
Intrinsic Robustness

Results

MTTD+MTTR = 5 min   Traffic = 500   160 sims per MTTF   CGR Routing   24 hrs







Walker constellation is **highly insensible** towards failures

But along-track actually was more reactive in **re-routing**

And still, along-track showed a larger **utilization of storage**

J. A. Fraire, P. Madoery, S. Burleigh, et al., "Assessing Contact Graph Routing Performance and Reliability in Distributed Satellite Constellations," Journal of Computer Networks and Communications, vol. 2017, Article ID 2830542, 18 pages, 2017. https://doi.org/10.1155/2017/2830542.

Intrinsic Robustness

Findings

- **Intrinsic Robustness in DTNs**
  - **Walker:** less hops, simpler routes................more robust
  - **Train:** multiple hops, complex routes...........less robust (data can be stuck)

- Faults are either
  - **Hidden in disconnection periods**.............(assuming reliable data storage)
  - **Blocking an expected contact**............... (success depends on **re-routing**)

Smart Re-routing

Towards Uncertain DTNs

- Redundancy:
  - Spatial/Time: **Copies**

Smart Re-routing

- Redundancy:
  - Spatial/Time: **Copies**
- **Probabilistic DTNs**
  - **Infer, learn from patterns**
  - i.e., Prophet, Spray-and-Wait

Copies

- **Scheduled DTNs**
  - **Rely on an accurate plan**
  - i.e., CGR

No copies

Smart Re-routing

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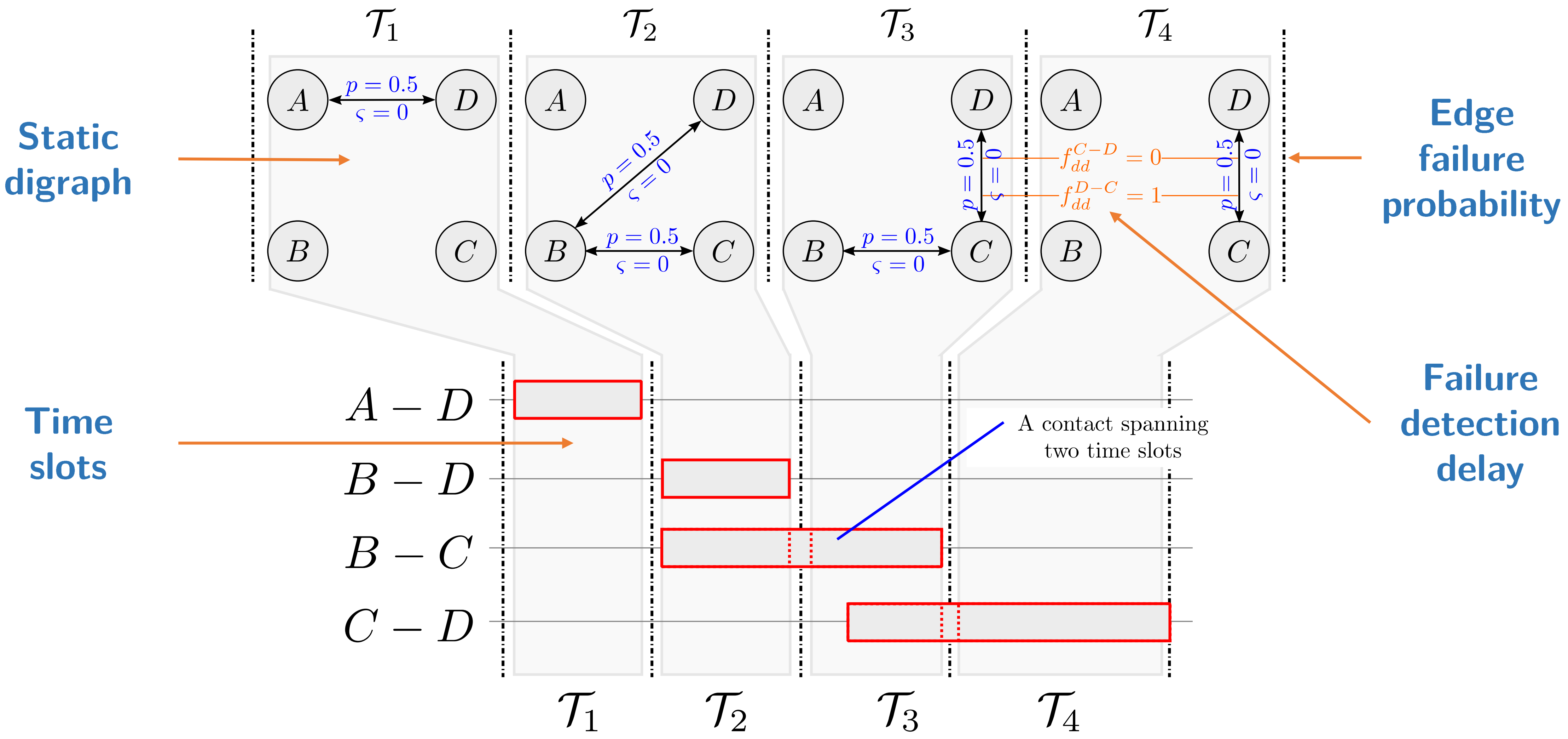
  - **Uncertain contact plans**

Copies

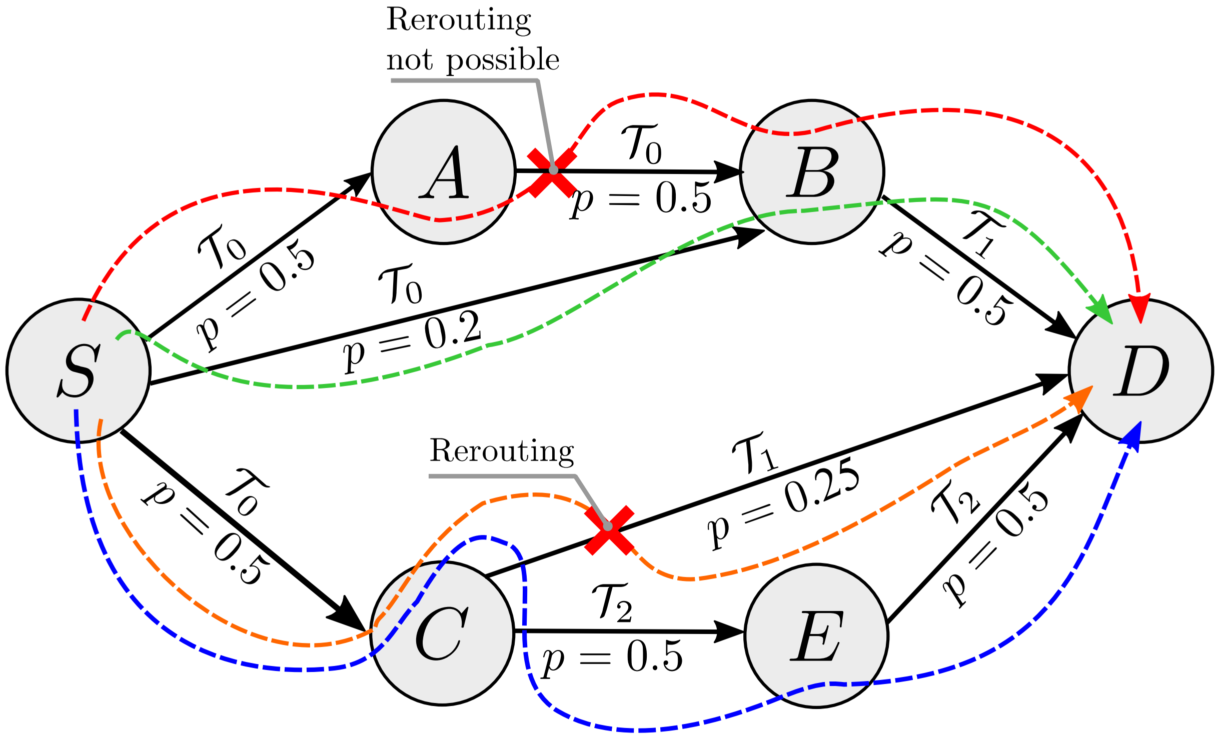
Smart Re-routing

Network Model



Smart Re-routing

Re-routing



Failure detection delay = 1 for all links

Successful Delivery Probability

SDP $= 0.5 * 0.5 * 0.5 = 0.125$

SDP $= 0.2 * 0.5 = 0.1$

SDP $= 0.5 * 0.25 = 0.125$

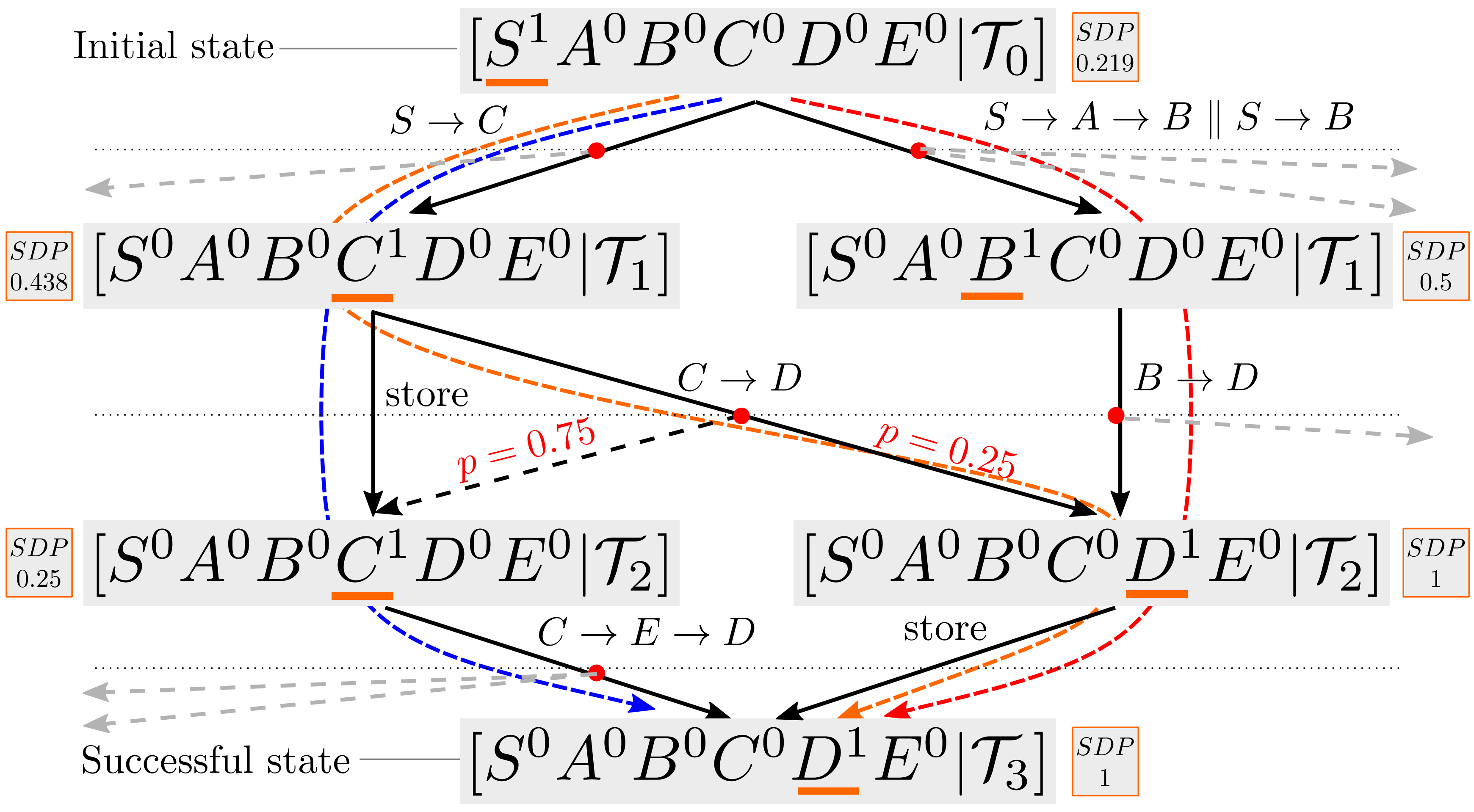
SDP $= 0.5 * (0.25 + 0.75 * 0.5 * 0.5) = 0.219$

Smart Re-routing

- We want to decide on most **reliable routes**
  - At any node, at any time
  - Considering **re-routing delays**
  - Supporting **multiple copies**
- **Markov Decision Process (MDP)**
  - **Probabilistic** and **Non-deterministic** behavior
  - States, Actions, Probabilities, Reward
  - Efficient **solvers**
  - Optimal **policies** (routes with best SDP)

Smart Re-routing

Markov Decision Process – Single Copy



Smart Re-routing

Markov Decision Process – Multiple Copies

Initial state $[\underline{\underline{S}}^2 A^0 B^0 C^0 D^0 E^0 | \mathcal{T}_0]$

$$[S^0 A^0 \underline{\underline{B}}^2 C^0 D^0 E^0 | \mathcal{T}_1] \qquad [S^0 A^0 B^0 \underline{\underline{C}}^2 D^0 E^0 | \mathcal{T}_1]$$

$$[S^0 A^0 \underline{B}^1 \underline{C}^1 D^0 E^0 | \mathcal{T}_1]$$

(...)

Successful states

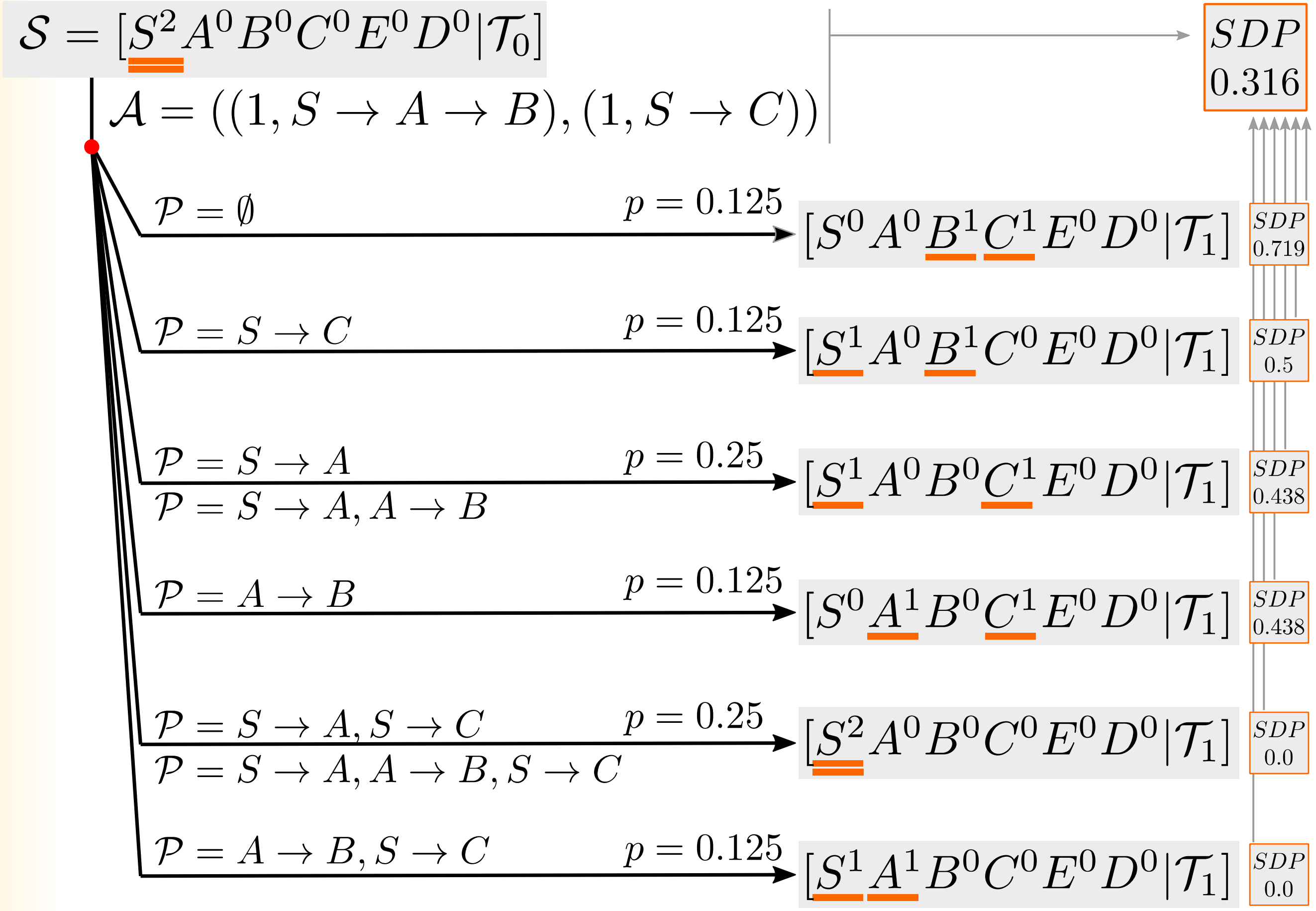
$$[\underline{S}^1 A^0 B^0 C^0 \underline{D}^1 E^0 | \mathcal{T}_3] \qquad [S^0 \underline{A}^1 B^0 C^0 \underline{D}^1 E^0 | \mathcal{T}_3]$$

$$[S^0 A^0 \underline{B}^1 C^0 \underline{D}^1 E^0 | \mathcal{T}_3] \qquad [S^0 A^0 B^0 \underline{C}^1 \underline{D}^1 E^0 | \mathcal{T}_3]$$

$$[S^0 A^0 B^0 C^0 \underline{\underline{D}}^2 E^0 | \mathcal{T}_3] \qquad [S^0 A^0 B^0 C^0 \underline{D}^1 \underline{E}^1 | \mathcal{T}_3]$$

Smart Re-routing

Routing Under Uncertain Contact Plans (RUCoP)



$\mathcal{A}_{SDP} = 0.125*0+0.25*0+0.125*0.438+0.25*0.438+0.125*0.5+0.125*0.719$

$\mathcal{A}_{SDP} = 0.316$

Algorithm 1: RUCoP Algorithm

Input: net, num_copies, sources, target, ς, f_{dd}
Output: a MDP

determine *successful states* $[\mathcal{S}]_{\mathcal{T}_{end}}$
for all $\mathcal{T}_i \in \mathbf{T}$, starting from $\mathcal{T}_{end-1}$ **do**
  $[\mathcal{S}]_{\mathcal{T}_i} \leftarrow \{\}$
  for all state $\mathcal{S} \in [\mathcal{S}]_{\mathcal{T}_{i+1}}$ **do**
    determine *carrier nodes* $[\mathcal{C}]_{\mathcal{T}_i}$
    for all node $\mathcal{C} \in [\mathcal{C}]_{\mathcal{T}_i}$ **do**
      for all node $\mathcal{N} \in pred^*([\mathcal{C}]_{\mathcal{T}_i})$ **do**
        $[\mathcal{R}^{SP}_{\mathcal{N},\mathcal{C}}] \leftarrow \{1, .., cp(\mathcal{C})\} * path^{\mathcal{T}_i \to \mathcal{T}_{i+1}}_{\mathcal{N} \to \mathcal{C}}(\varsigma)$
        $[\mathcal{R}^{MP}_{\mathcal{N},\mathcal{C}}] \leftarrow (\bigcup^{\leq cp(\mathcal{C})}_{k \in [1:cp(\mathcal{C})]} \binom{\mathcal{R}^{MP}}{k}) \cup \{\epsilon\}$
      end for
      $[\mathcal{R}_{\mathcal{C}}] \leftarrow \prod^{\leq cp(\mathcal{C})}_{n \in pred^*(\mathcal{C})} \mathcal{R}^{MP}_{n,\mathcal{C}}$
    end for
    for all $\mathcal{A} \in \prod^{\leq num\_copies}_{\mathcal{C} \in [\mathcal{C}]_{\mathcal{T}_i}, \mathcal{N} \in pred^*([\mathcal{C}]_{\mathcal{T}_i})} \mathcal{R}_{\mathcal{C}}$ **do**
      $\mathcal{S}_{\mathcal{T}_i} \leftarrow get\_previous\_state(\mathcal{S}, \mathcal{A})$
      if $SDP(\mathcal{S}_{\mathcal{T}_i}) < SDP(\mathcal{A}, \mathcal{S}_{\mathcal{T}_i}, \varsigma, f_{dd})$ **then**
        $SDP(\mathcal{S}_{\mathcal{T}_i}) = SDP(\mathcal{A}, \mathcal{S}_{\mathcal{T}_i}, \varsigma, f_{dd})$
        $best\_action(\mathcal{S}_{\mathcal{T}_i}) = \mathcal{A}$
      end if
      $[\mathcal{S}]_{\mathcal{T}_i} \leftarrow \mathcal{S}_{\mathcal{T}_i}$
    end for
  end for
end for

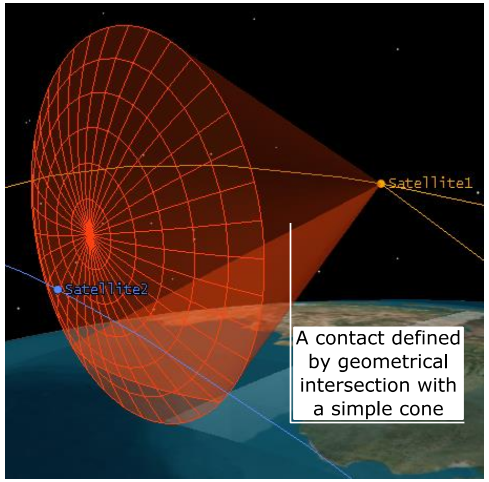
Smart Re-routing

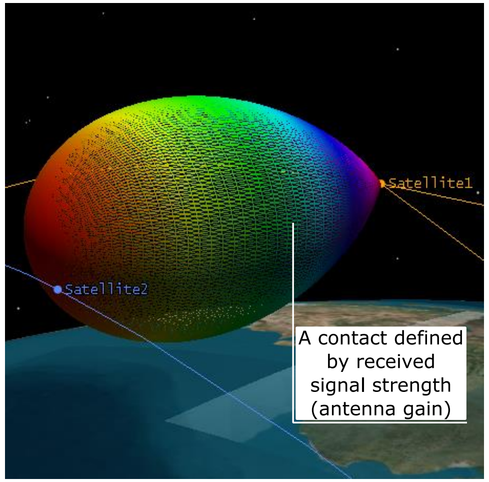
Tools and Methodology

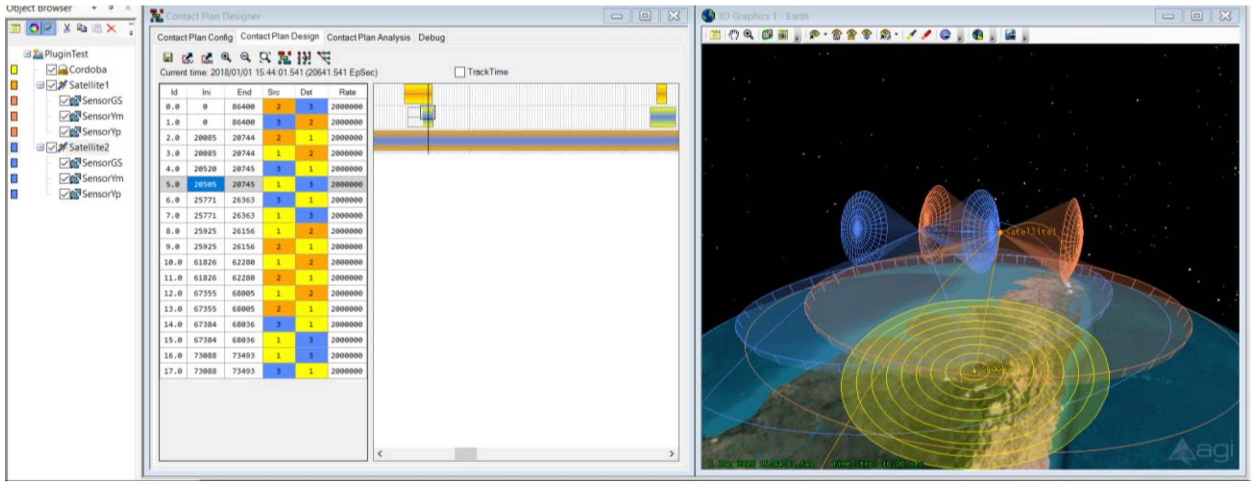
- **Contact Plan Designer**
  - **Planning:** compute uncertain contact plans
  - STK **propagators** & **comms. Models**
  - Constellation designer
  - Centralized **routing calculator**

Spinning off

Outputs for DtnSim, ION, μPCN, csv, etc.



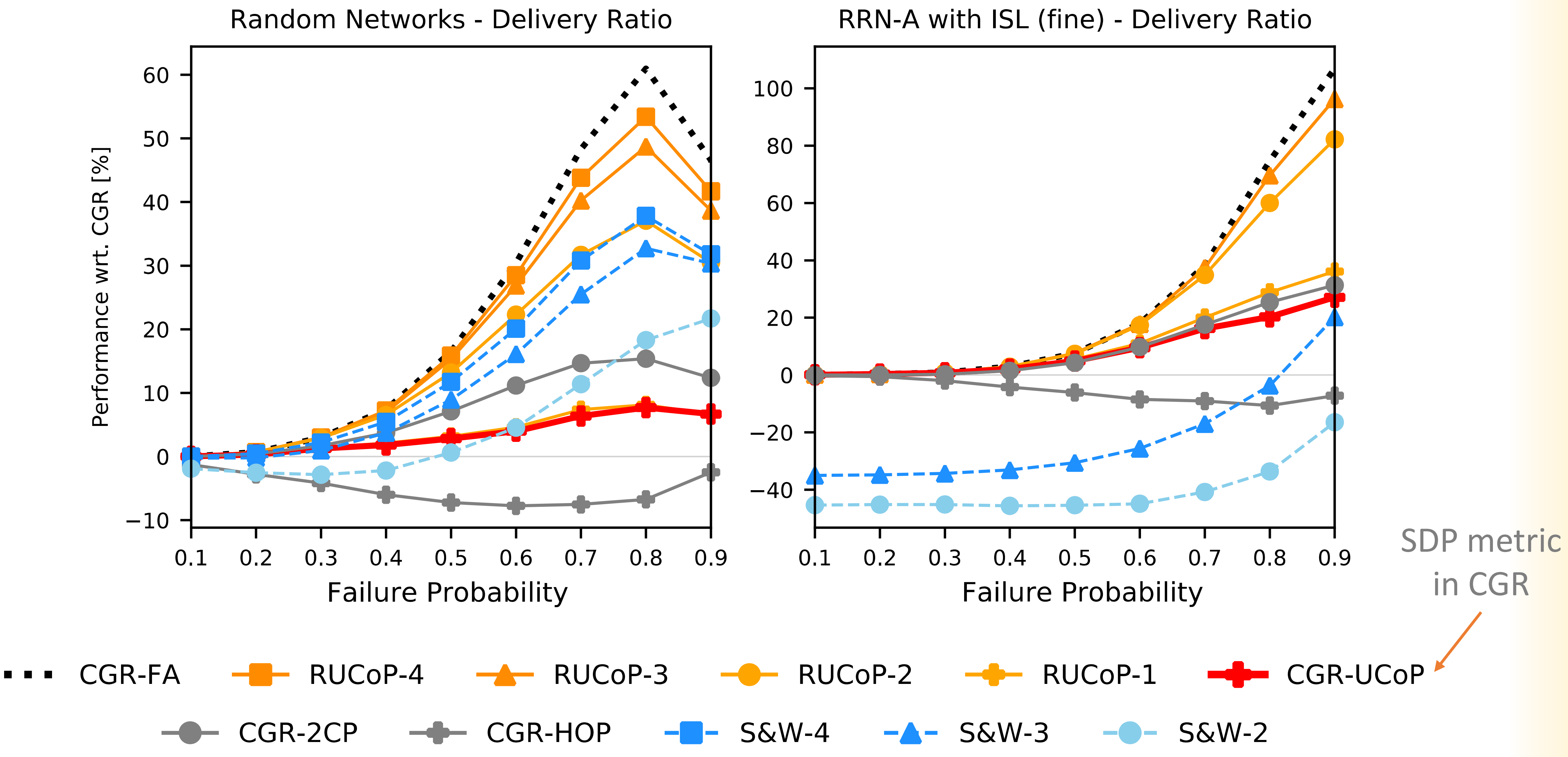




J. A. Fraire, "Introducing Contact Plan Designer: A Planning Tool for DTN-Based Space-Terrestrial Networks," 2017 6th International Conference on Space Mission Challenges for Information Technology (SMC-IT), Alcala de Henares, 2017, pp. 124-127. doi: 10.1109/SMC-IT.2017.28

Smart Re-routing

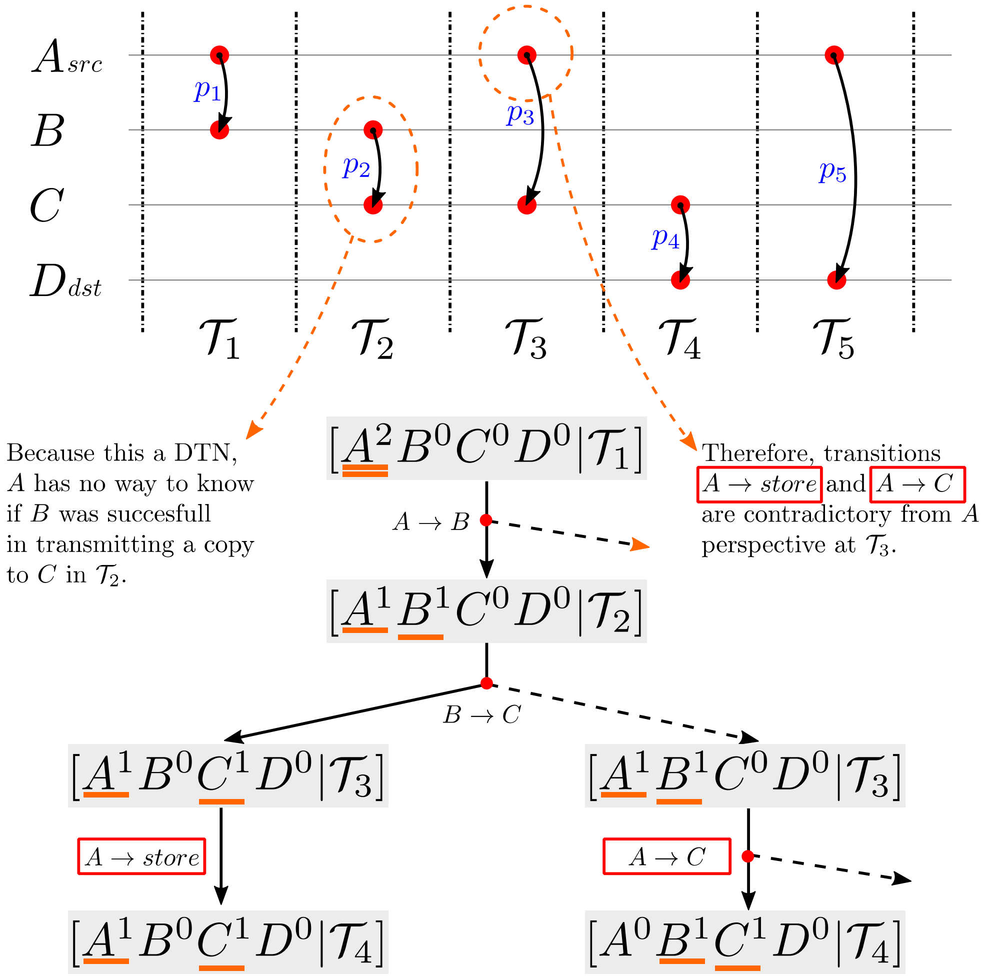
Results



Smart Re-routing

Towards a Local Scheduler

- **Current MDP:** global scheduler
  - Real DTNs: local scheduler
- **Hidden MDP**
  - Results to come ☺



Closing Remarks

- Current space context is **as exiting as it gets**
- Networking the “new space” requires novel approaches
  - **Delay-Tolerant Networking**
  - **Intrinsic robustness** & **smart re-routing**
- But uncertainties are just one aspect of the overall story:
  - **Medium Access**
  - **Congestion**
  - **Scheduling** (battery, interference, etc.)
  - **Scalability** (regions, simplifications)
  - **Applications...**

Closing

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Thank you!

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Satellite Constellation Designer

STK Plugin

By J. Fraire

Backup Slides

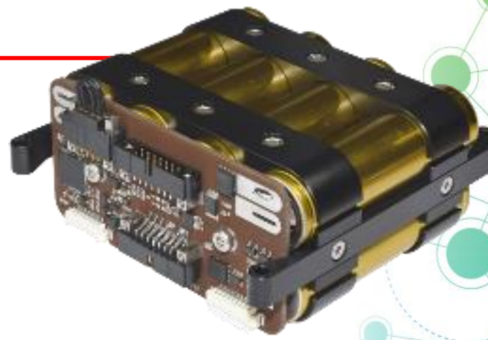
References

- J. A. Fraire and P. A. Ferreyra, "Assessing DTN architecture reliability for distributed satellite constellations: Preliminary results from a case study," *2014 IEEE Biennial Congress of Argentina (ARGENCON)*, Bariloche, 2014, pp. 564-569. doi: 10.1109/ARGENCON.2014.6868551
- J. A. Fraire, P. Madoery, S. Burleigh, et al., “Assessing Contact Graph Routing Performance and Reliability in Distributed Satellite Constellations,” Journal of Computer Networks and Communications, vol. 2017, Article ID 2830542, 18 pages, 2017. https://doi.org/10.1155/2017/2830542.

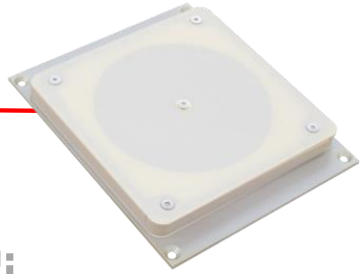
Coms and Power Subsystems

- NanoCom SR2000
  - SDR
  - Xilinx Zynq7000 FPGA
  - Avg. Power Consumption: **6 W**

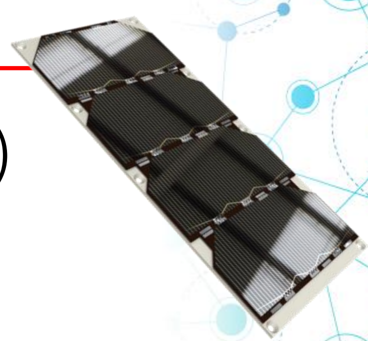
- NanoPower BPX
  - Lithium ion cells (**77 Wh**)
  - Heaters **6W**



- ANT2000
  - Power Consumption: **10 W**
  - Tx power Pt: 1.6W, gain: **8dBi**



- NanoPower P110
  - Power on sunlight exposure (**15 W**)



In **5 hs of eclipse** (namely 4 orbits), **battery is fully discharged** (77 Wh)

Battery-Aware Model

MILP MODEL PARAMETERS

Input Coefficients	
N	Nodes quantity
K	Topology states quantity
$\{t_k\}$	State k start time $(1 \leq k \leq K)$
$\{i_k\}$	State k duration $(i_k = t_k - t_{k-1} : 1 \leq k \leq K)$
$\{x_{k,i,j}\}$	Capacity of i to j contact at state k $(1 \leq k \leq K$ and $1 \leq i,j \leq N)$
$\{b_{max,i}\}$	Maximum buffer capacity at node i $(1 \leq i \leq N)$
$\{d_k^{i,j}\}$	Traffic from i to j originated at the beginning of k $(1 \leq k \leq K$ and $1 \leq i,j \leq N)$
$\{p_i\}$	Max. simultaneous links in node i $(1 \leq i \leq N)$
M	Big "M" coefficient for interface decision equations
$\{c_{min,i}\}$ $\{c_{max,i}\}$	Minimum and maximum battery charge at node i $(1 \leq i \leq N)$ at all times
$\{c_{0,i}\}$	Initial battery charge at node i
$\{c^i_{rC}\}$	Battery recharge rate because of sunlight exposure at node i, if on eclipse, then this coefficient shall be 0
$\{c^i_{rT}\}$	Battery consumption rate because of transmission or reception system enabled at node i
$\{c^i_{rB}\}$	Battery consumption rate because of background load at node i

Output Variables	
$\{X^{y,z}_{k,i,j}\}$	Traffic from y to z at state k flowing in i to j edge $(1 \leq i,j,y,z \leq N)$
$\{B^{y,z}_{k,i}\}$	Node i buffer occupancy at the end of state k by the traffic flow from y to z $(1 \leq i,y,z \leq N)$
$\{Y_{k,i,j}\}$	Binary variable for interface selection from i to j at state k $(1 \leq k \leq K$ and $1 \leq i,j \leq N)$
$\{C_{k,i}\}$	Battery charge at node i at the end of state k $(1 \leq k \leq K$ and $1 \leq i,j \leq N)$

Multi commodity flow formulation

+

GOM-X4 **Linear battery Model** (LiBaM)

$$\sum_{j=1}^{N} X^{y,z}_{k,j,i} - \sum_{j=1}^{N} X^{y,z}_{k,i,j} = B^{y,z}_{k,i} - (B^{y,z}_{k-1,i} + d^{i,z}_k) \quad \forall k,i,y,z \tag{2}$$

$$B^{y,z}_{k,i} <= b^i_{max} \quad \forall k,i,y,z \tag{3}$$

$$B^{y,z}_{0,i} = 0 \quad \forall i,y,z \tag{4}$$

$$\sum_{y=1}^{N}\sum_{z=1}^{N} X^{y,z}_{k,i,j} <= x_{k,i,j} \quad \forall k,i,j \tag{5}$$

$$\sum_{k=1}^{K}\sum_{j=1}^{N} X^{y,z}_{k,i,j} = \sum_{k=1}^{K} d^{i,j}_k \quad \forall i = y,z \tag{6}$$

$$\sum_{k=1}^{K}\sum_{i=1}^{N} X^{y,z}_{k,i,j} = \sum_{k=1}^{K} d^{i,j}_k \quad \forall y,j = z \tag{7}$$

$$\sum_{j=1}^{N} Y_{k,i,j} <= p_i \quad \forall i,k \tag{8}$$

$$\sum_{j=1}^{N}\sum_{y=1}^{N}\sum_{z=1}^{N} X^{y,z}_{k,i,j} <= M * Y_{k,i,j} \quad \forall i,k \tag{9}$$

$$C_{0,i} = c_{0,1} \quad \forall i \tag{10}$$

$$c^i_{min} <= C_{k,i} <= c^i_{max} \quad \forall k,i \tag{11}$$

$$C_{k,i} <= C_{k-1,i} + (c^i_{rC} - c^i_{rB} - c^i_{rT}\sum_{j=1}^{N} Y_{k,i,j}) * t_k \quad \forall k,i$$

Skyloom

Smart Re-routing

Routing Under Uncertain Contact Plans (RUCoP)