

A tool suite towards a Solar System Internet digital twin

PhD kick-off presentation

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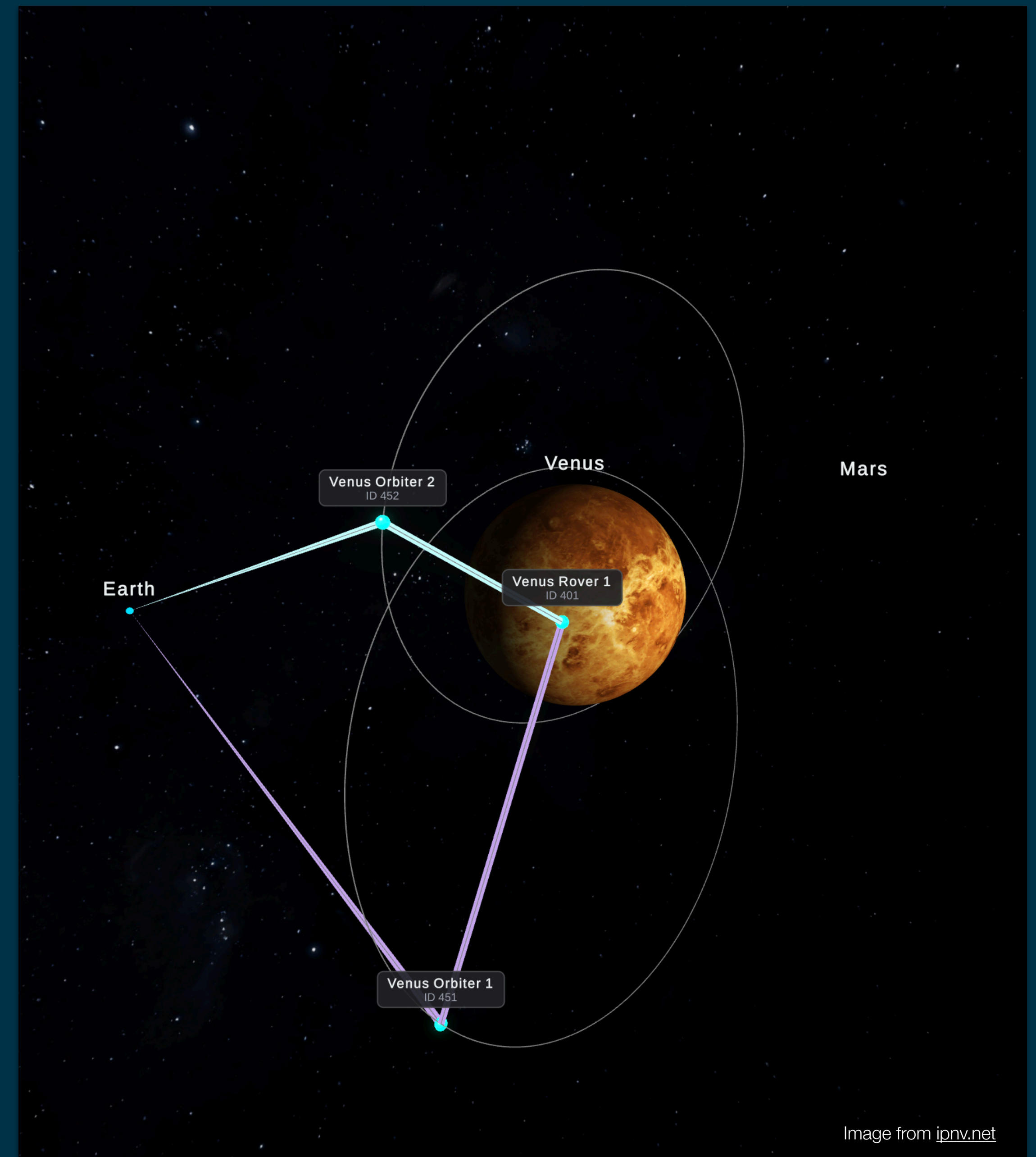


Image from ipnv.net

Why do we need a "Solar System Internet" ?

Increase in the number of deep space missions :

- Shift from point-to-point communications to an **interoperable, standardised Internet-like architecture** [1]
- Space communications constraints [2] :
 - long **propagation delays**
 - **planned intermittent connectivity**, many space assets are disconnected most of the time except during specific contact windows
 - **asymmetry** between UL and DL capacities
- ➔ The envisioned Solar System Internet (SSI) leverages **Delay-Tolerant Networking** (DTN) [3] and the standardised **Bundle Protocol** (BP) [4]

The Solar System Internet at ESA

- **ESA Strategy 2040** includes strategic actions for the Solar System Internet [5]
- DTN and BP are mature technologies... but we need to **transfer those into operations**
- Mission operations will change: **mission-specific decisions will have a network-wide impact**



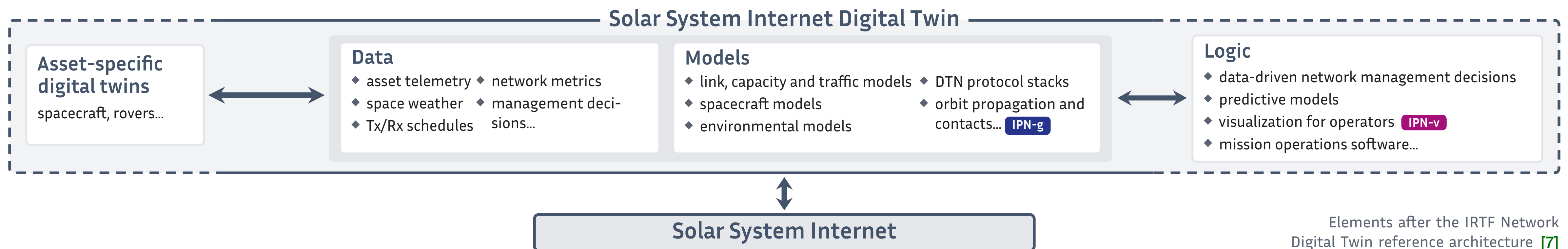
Front page of the ESA Strategy 2040 document [5]

Preparing and operating the SSI

Need a **widely accessible framework** for **monitoring**, **analysing**, and **predicting** the behaviour of the SSI:

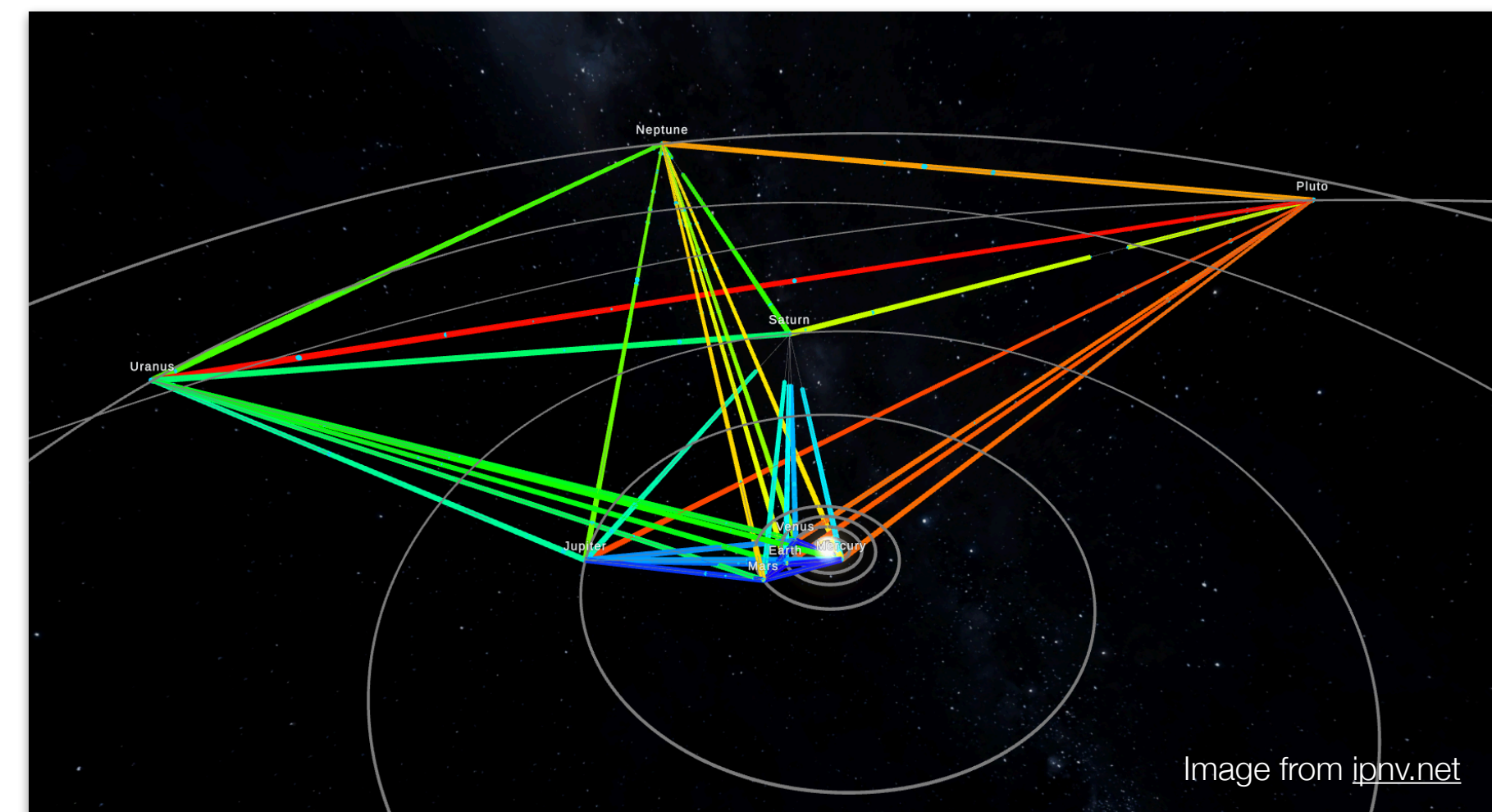
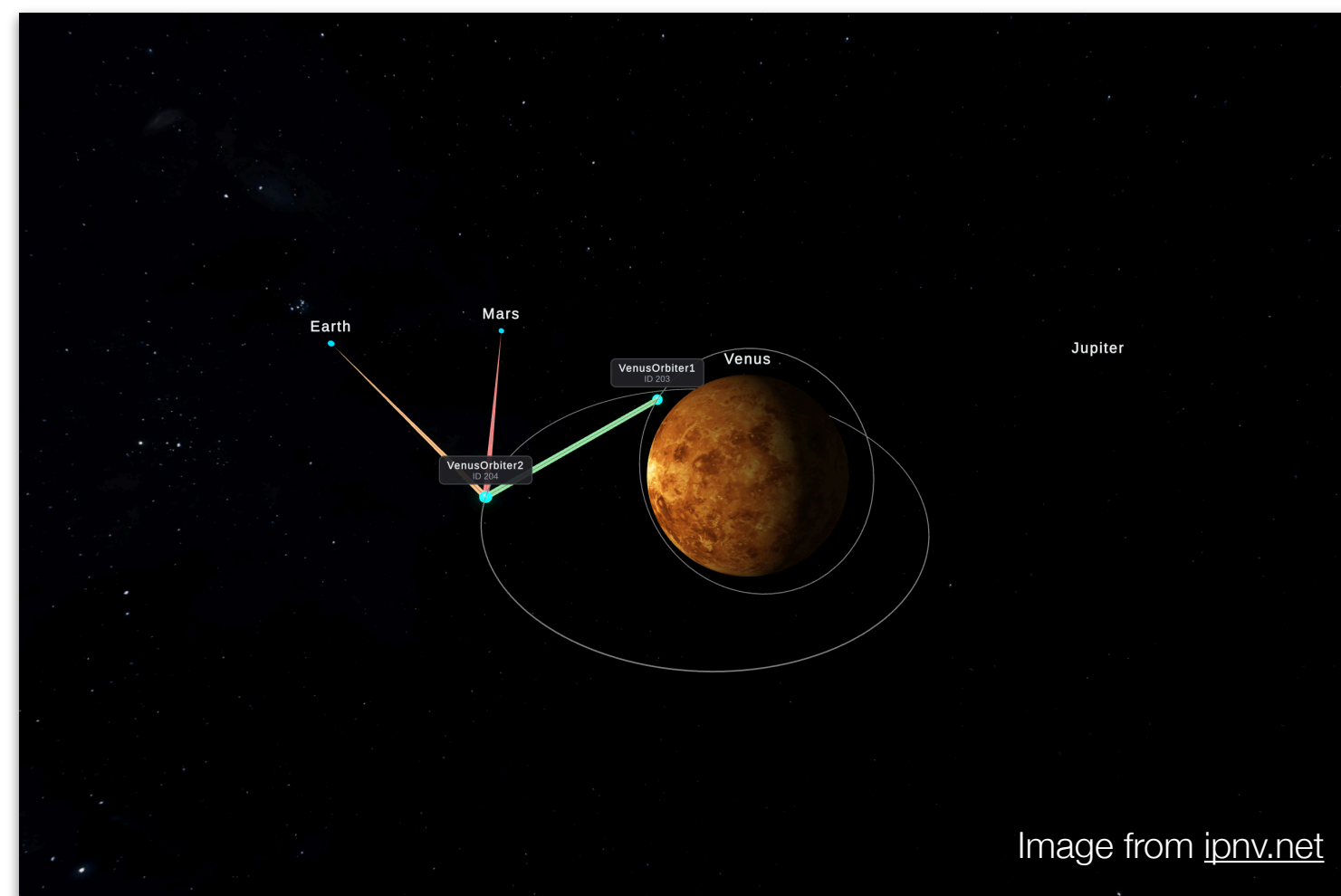
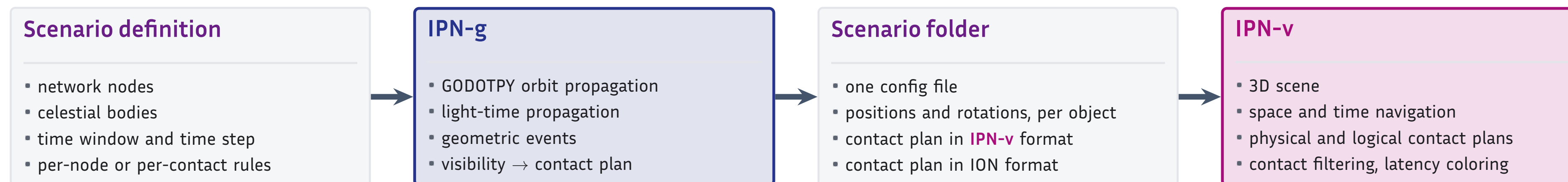
- **Emulating** the network under **highly realistic conditions**
- Integrating **real-time operational data**, eventually closely mirroring the current state of the real network
- Running in **standalone sandbox mode**

➔ A possible architecture approach is the **digital twin**



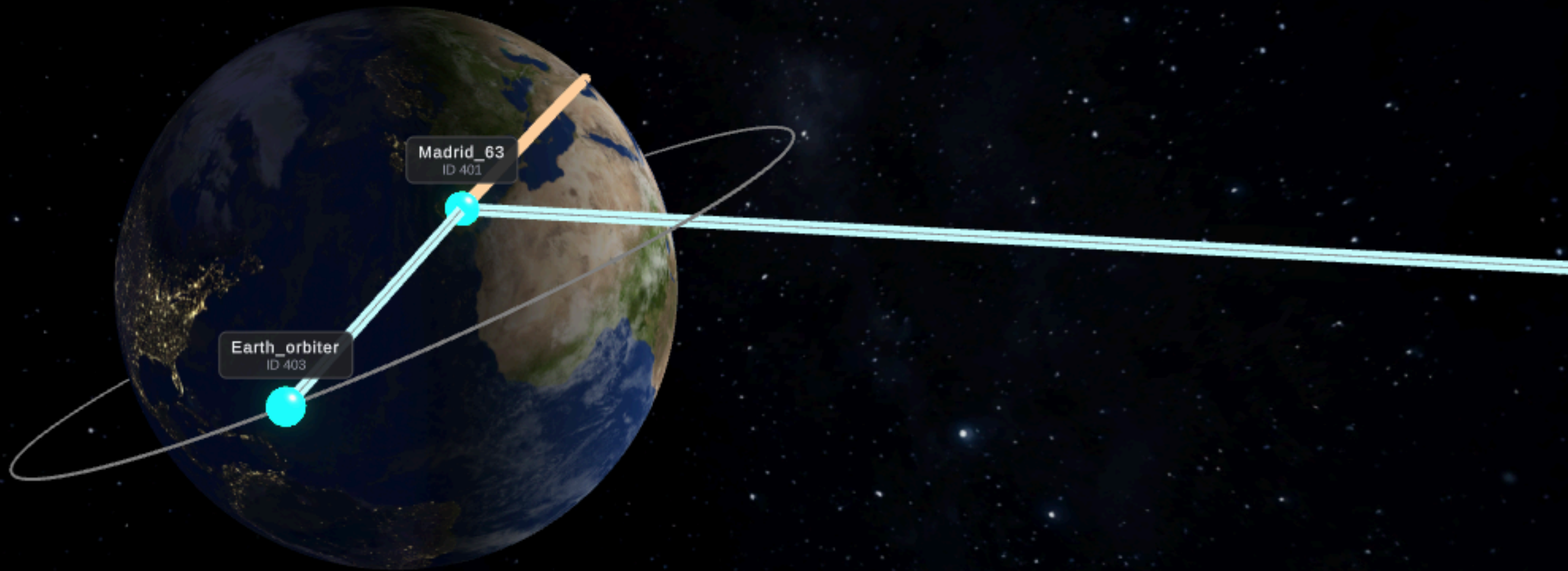
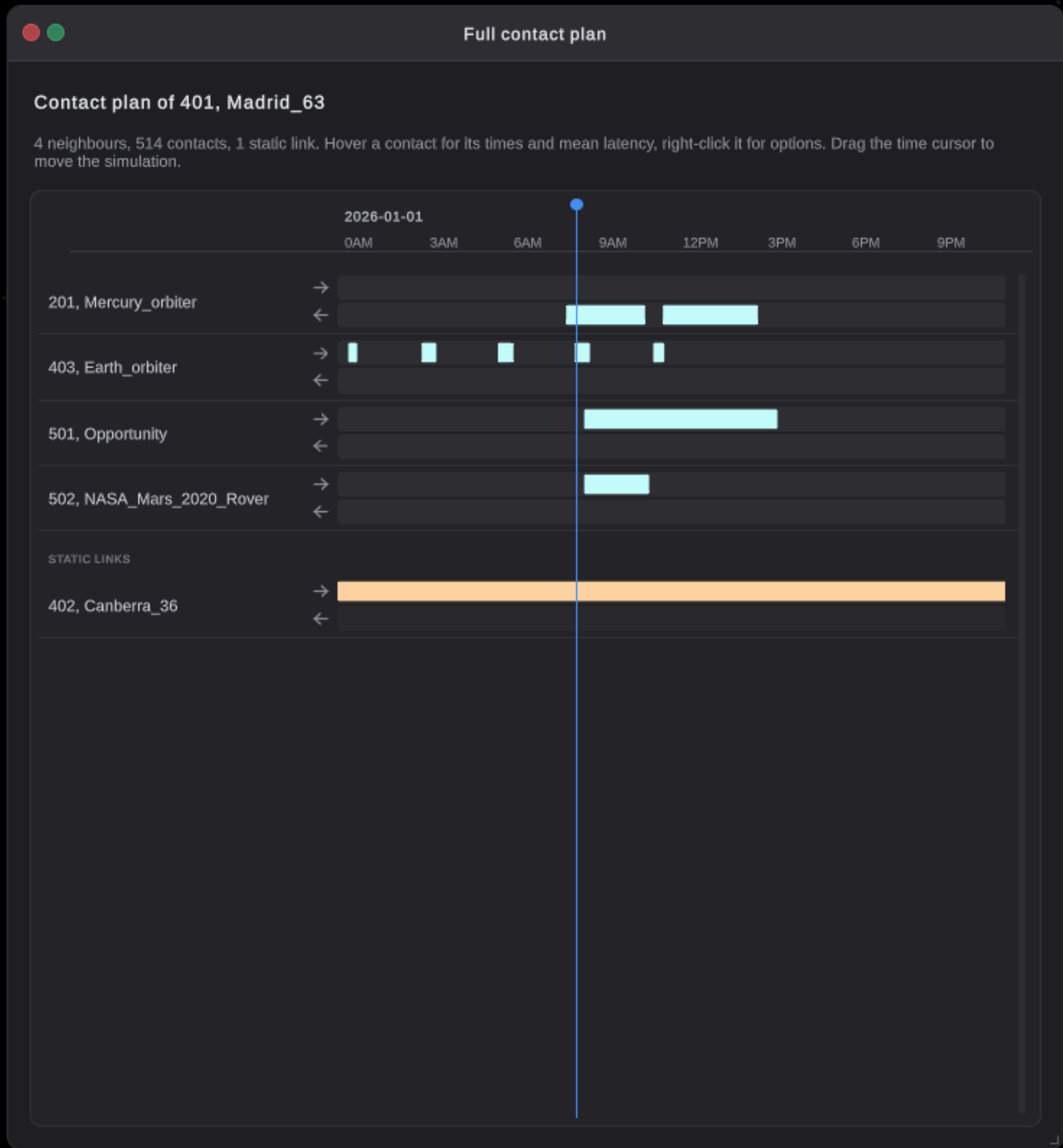
Zoom on IPN-g and IPN-v

IPN-g for high-fidelity Interplanetary Network scenario generation and **IPN-v** [6] for 3D contact plan visualisation



Zoom on IPN-g and IPN-v (cont'd)

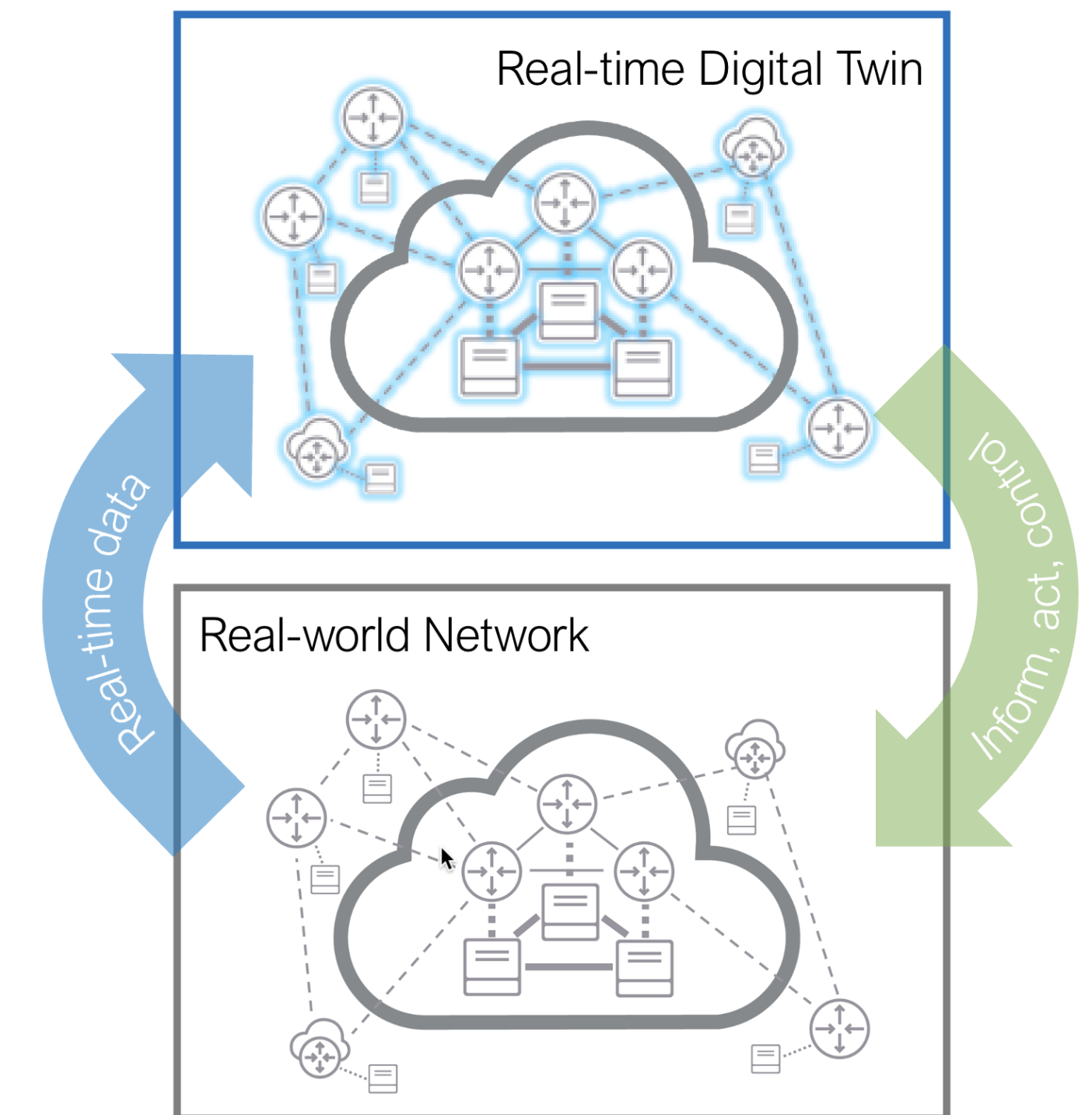
Image from ipnv.net



Network Digital Twins

From the Internet Research Task Force, a Network Digital Twin [7] :

- Relies on **bi-directional** communication with the physical network
 - Collects, aggregates and analyses **real-time TM** from the physical network
 - Takes **data-driven network management decisions** and **automatically issues control commands**
 - Allows to explore "**what-if**" **scenarios**, simulate **end-of-life**, test **new protocols** or **network policies**, train operators...
- ➔ Particularly valuable in the space context to perform **independent tests without operational risks or expenses**



Representation of a Network Digital Twin ([source](#))

A delay-tolerant digital twin

Applying the Network Digital Twin architecture to the SSI requires significant adaptations:

- Digital twins typically rely on **high-speed** and **high-availability** links for **quick synchronisation**
 - There is no **guarantee of continuous end-to-end connectivity** and **timely communications** in the SSI
- ➔ **Delayed TM/TC data exchanges** between the real and twin networks
- ➔ The **SSI digital twin itself** and the **network management processes** must be **delay-tolerant**

Building Delay-Tolerant Digital Twins for Cislunar Operations using Age of Synchronization

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RFC 9675: Delay-Tolerant Networking Management Architecture (DTNMA)

DTN

E. Birrane, III, S. Heiner, E. Annis

INFORMATIONAL

Digital Twin for Non-Terrestrial Networks: Vision, Challenges, and Enabling Technologies

Hayder Al-Hraishawi, *Senior Member, IEEE*, Madyan Alsenwi, *Member, IEEE*,
Junaid ur Rehman, Eva Lagunas, *Senior Member, IEEE*, and Symeon Chatzinotas, *Fellow, IEEE*

Mitigating data staleness

Improve the **delay-tolerance of a Network Digital Twin** facing substantial delays by [8]:

- Ensuring **high modelling accuracy** to reliably predict the network state when fresh data isn't available
- Efficiently **scheduling** telemetry information [9]
- **Compressing telemetry** [10] and **prioritising critical information** [11]
- Performing **machine learning on historical data**

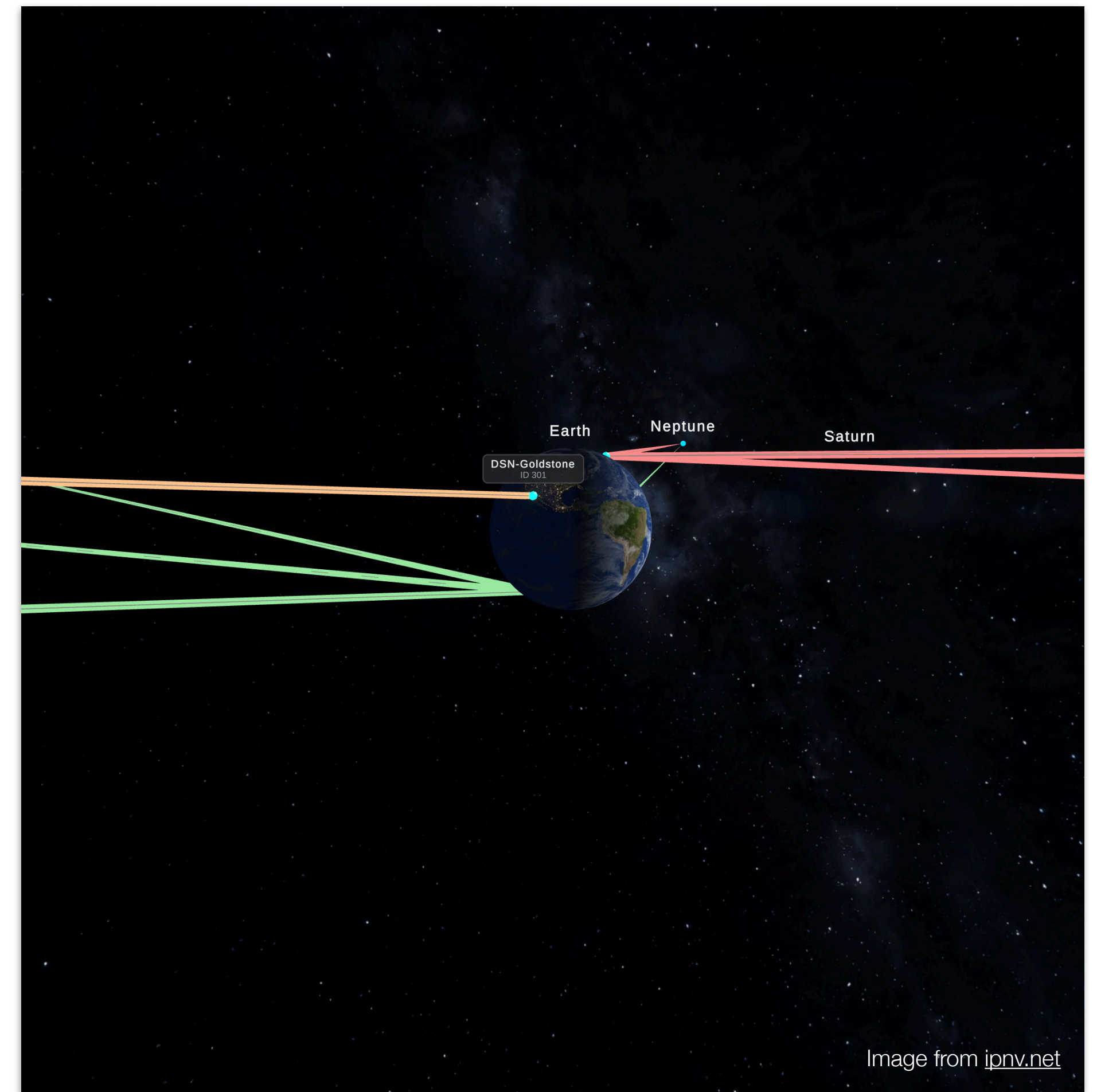
Urgency Reliability	Quasi-Real-Time Comms		Store-and-Forward Comms	
	Priority 1	Priority 2	Priority 1	Priority 2
No Losses	Critical (e.g. Astronaut Health Data)	Quasi-Real-Time, High Interaction (e.g. Voice)	Excellent Effort (e.g. Telemetry)	
Losses Acceptable		Quasi-Real-Time, Low Interaction (e.g. Video Streaming)	Best Effort (e.g. Sensor Data)	Bulk (e.g. Science Data)

Traffic priority grid for the Bundle Protocol [11]

Conclusion and next steps

Next steps include:

- Space and ground **asset models**, **data sources** and **network metrics** selection
 - **Modular digital twin architecture**, **data repository** and **interoperable interfaces** definition
 - Functional models for network **data analysis** definition
 - Definition of **performance and synchronisation metrics** for the twin, and **evaluation scenarios**
- ➔ **Evaluate and optimise SSI technologies with the digital twin**
- ➔ **Mitigate delays by giving operators awareness based on estimated states**



Thank you for your attention :)

Questions?

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- [2] S. Burleigh et al. *Delay-tolerant networking: an approach to interplanetary Internet*. IEEE Communications Magazine, vol. 41, no. 6, pp. 128-136. 2003.
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- [4] S. Burleigh, K. Fall, E. Birrane. RFC 9171 - *Bundle Protocol Version 7*. Internet Engineering Task Force.
- [5] European Space Agency. *ESA Strategy 2040 - In depth*. 2025.
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- [7] Cheng Zhou et al. Internet-Draft - *Network Digital Twin: Concepts and Reference Architecture*. Internet Research Task Force. 2026.
- [8] Hayder Al-Hraishawi et al. *Digital Twin for Non-Terrestrial Networks: Vision, Challenges, and Enabling Technologies*. ArXiv preprint: arXiv:2305.10273. 2023.
- [9] F. D. Quazi et al. *Building Delay-Tolerant Digital Twins for Cislunar Operations using Age of Synchronization*. 2024 IEEE International Conference on Communications Workshops (ICC Workshops), Denver, CO, USA, 2024, pp. 153-158.
- [10] E. Birrane, S. Heiner and E. Annis. RFC 9675 - *Delay-Tolerant Networking Management Architecture (DTNMA)*. Internet Engineering Task Force.
- [11] T. A. Ulierte et al. *Enabling Traffic Prioritization for Space Communications Over DTNs*. IEEE Journal of Radio Frequency Identification, vol. 8, p. 748-760, 2024.