Chair of Connected Mobility
School of Computation, Information and Technology
Technische Universität München

Networking in Space (WiSe 2025/26)

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Chair of Connected Mobility

https://www.ce.cit.tum.de/cm/

Course Pre-Meeting

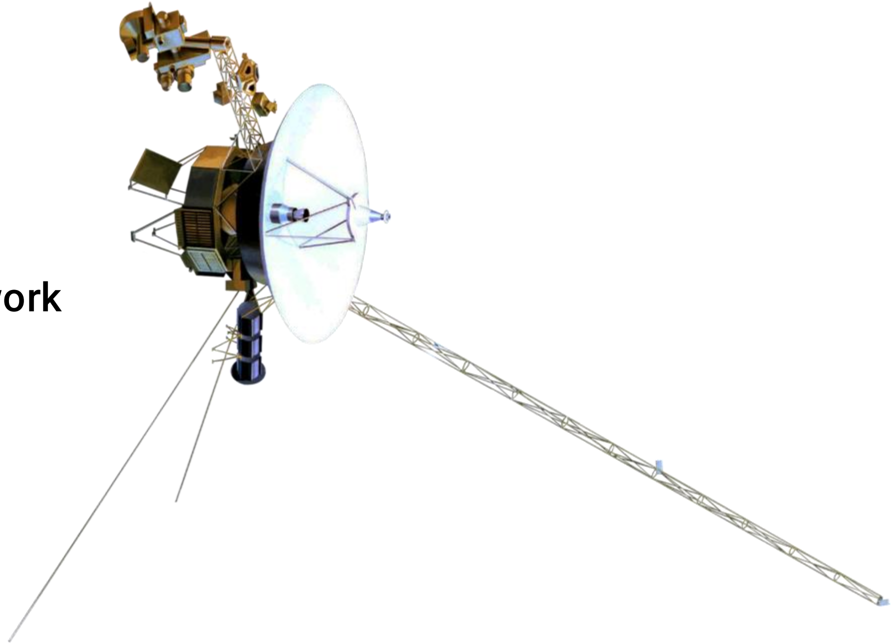
17 July 2025

Communication in Space – Then…

Example

- Voyager 1
  - Launched Sep 1977

- Deep space communication
  - Point-to-point link to the Deep Space Network
  - Right now at 160 bit/s
  - Earlier: 115 kbit/s



… And Now

- Perseverance Rover
  - Launched July 2020 – Landed Feb 2021
- Communications
  - UHF antenna
    - Data to Earth through Mars Orbiters
    - Up to 2 Mbps
  - X-band high-gain antenna
    - Data directly to/from Earth
    - Up to 800/3000 bps
  - X-band low-gain antenna
    - Receiving data from Earth
    - Up to 30bps

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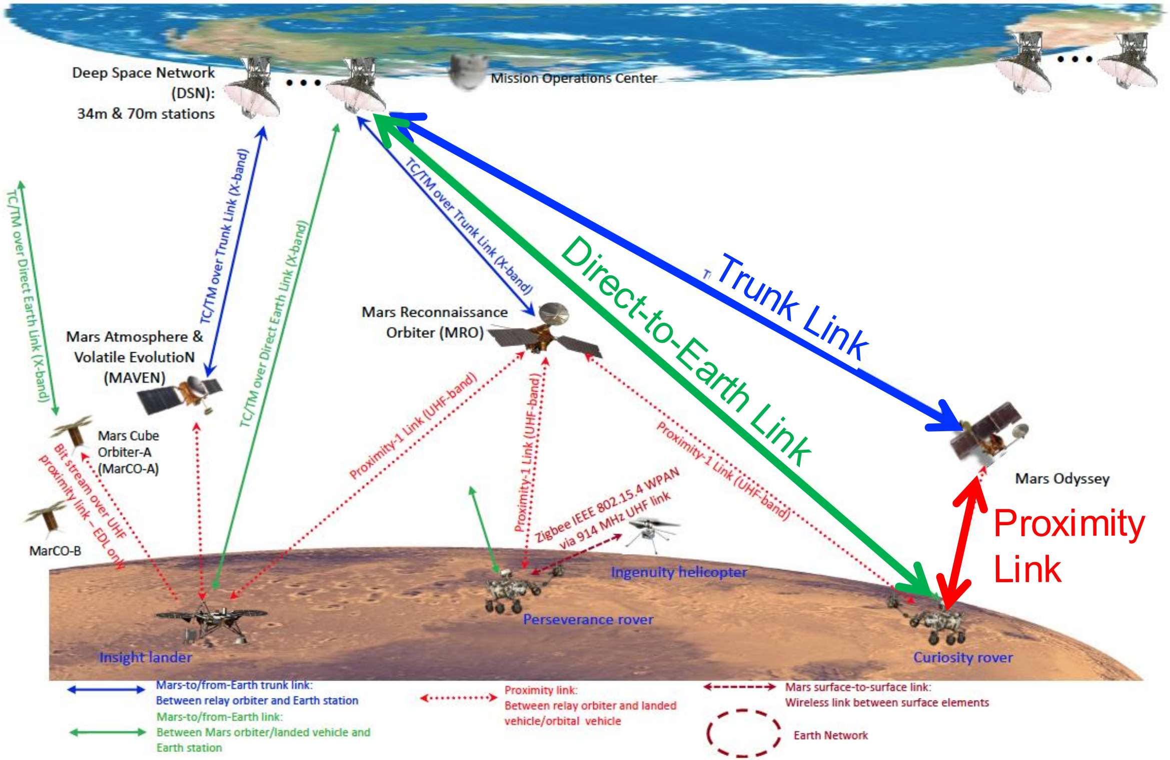
Mars Exploration



Deep Space Network (DSN)
– limited capacity (0.6–12 Mbps)

Mars science orbiters: 8
– only relay to surface assets
– one surface asset at a time
– short-lived connectivity
– 2 Mbps, no cross links

Mars Surface vehicles: 5
– no persistent links in-between

No end-to-end networking
Manual access config

Source: Mars and Beyond Communications Architecture Working Group, Interagency Operations Advisory Group, "The Future Mars Communications Architecture, Report of the Interagency Operations Advisory Group", February 2022.

Space is getting busier

- More nation states + international cooperation
- Commercial players
  - For launches, satellite networks, space mining
- More spacecraft
- More and growing missions
  - Lunar base
  - Mars outpost
  - Asteroid exploration

2018–2030 timeframe
> 40 missions
> 80 space vehicles
10 space agencies
+ commercial endeavors

2020–2040 timeframe
~ 40 missions
~ 63 spacecraft / vehicles
10 space agencies
+ commercial endeavors

- Interoperability and infrastructure reuse desirable → (inter)networking
  - Cross support among agencies already well-established

Mars Relay Network

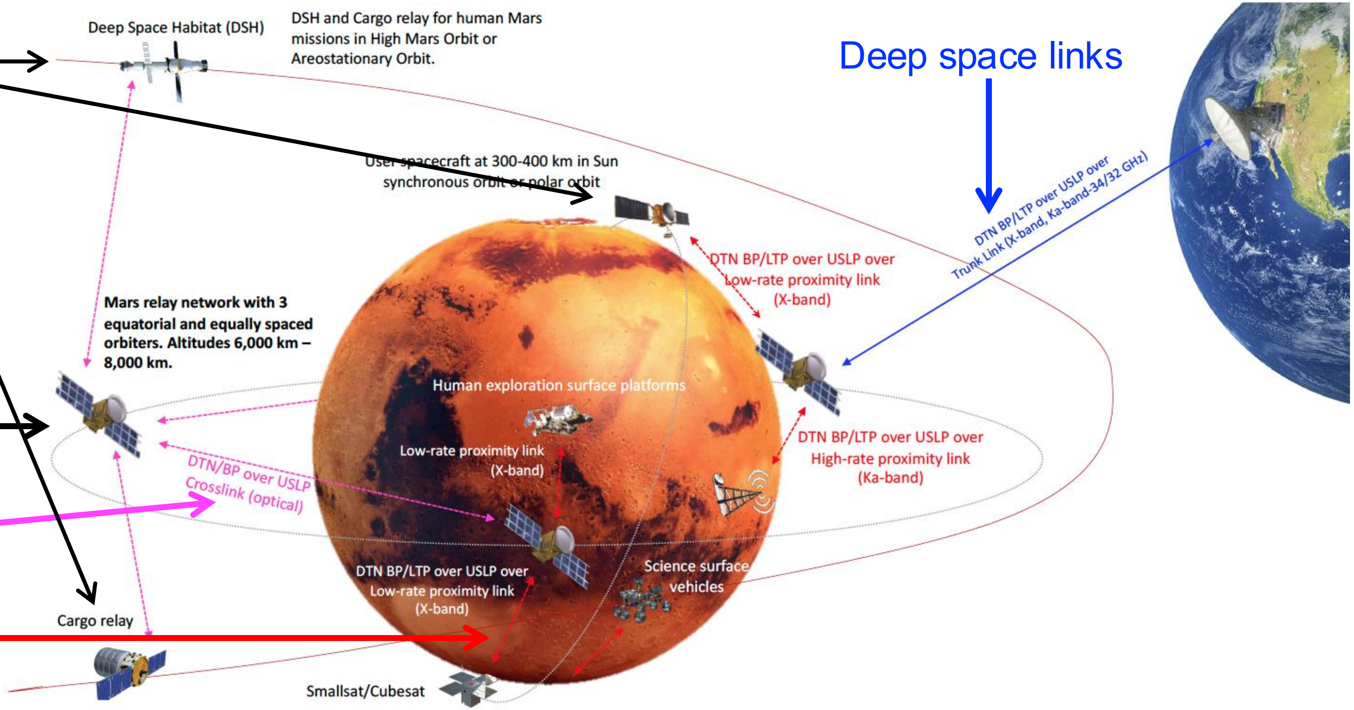
Connect and augmented by other units

Small constellation of dedicated relays

Optical cross links

Proximity links to the surface

Deep space links



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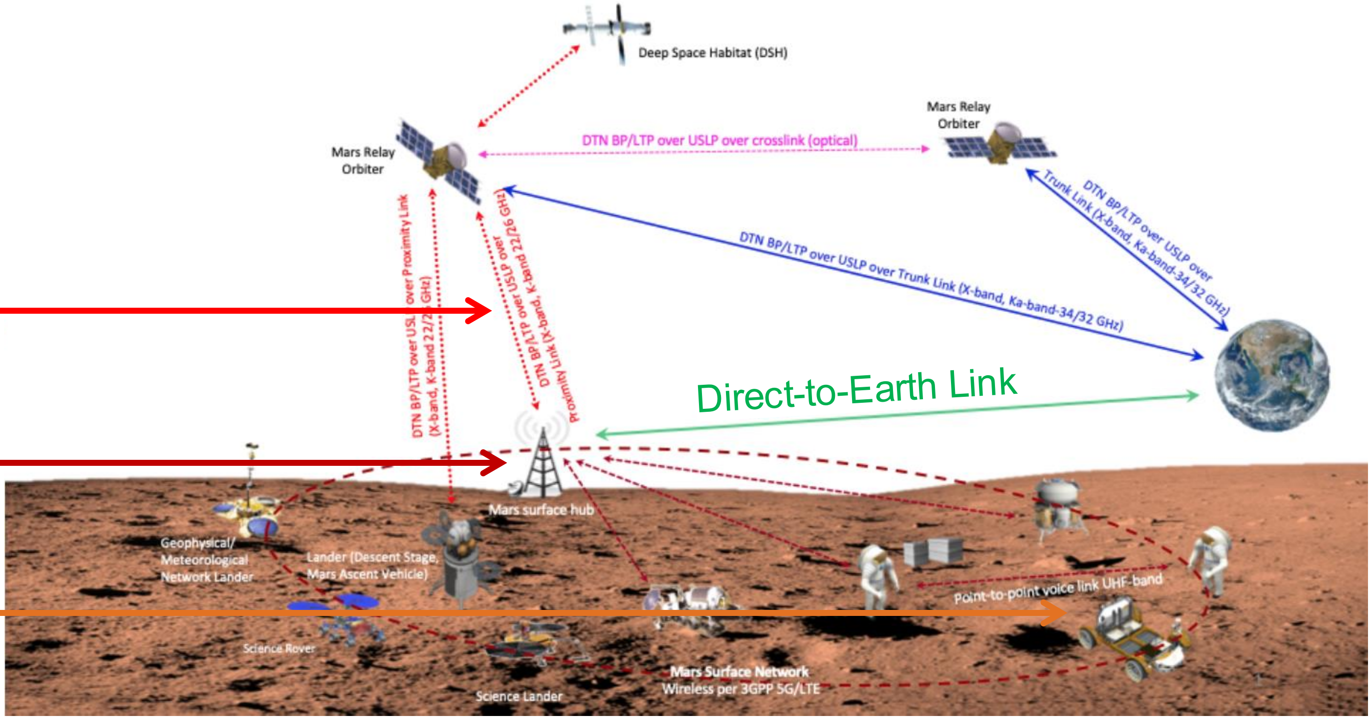
Mars Surface Network

Proximity links to the surface

Infrastructure surface network (LTE / 5G / Wi-Fi)

Ad-hoc networks (Wi-Fi, ZigBee, …)



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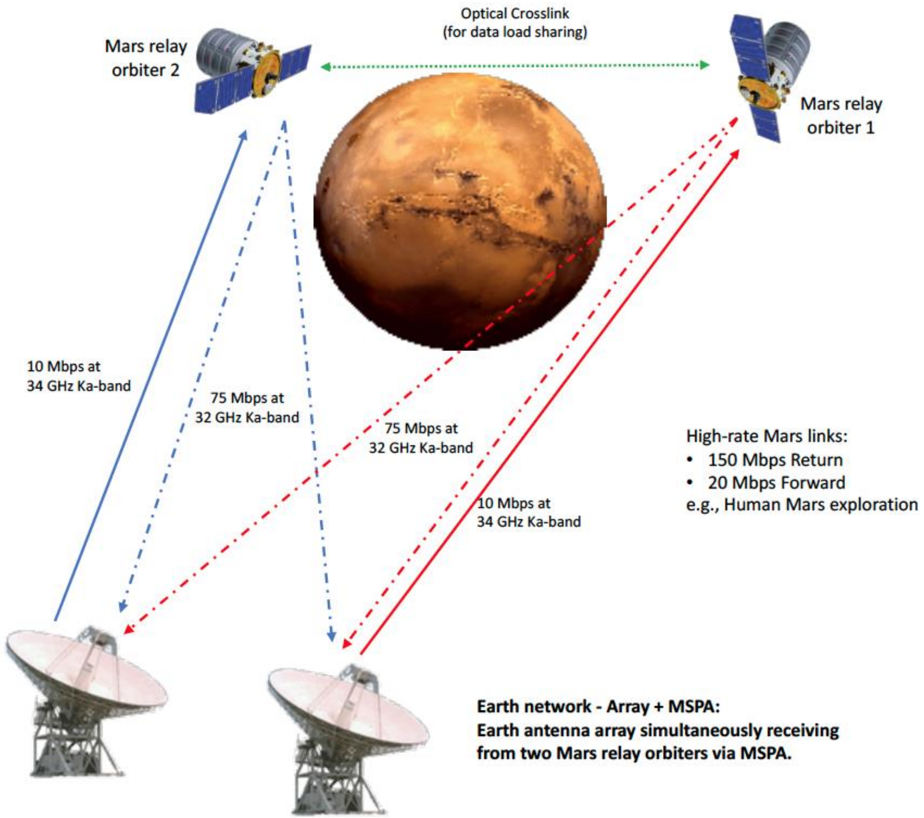
Talking to Earth

- 29 Earth stations deployed today
  - Cross support (agencies, commercial)
  - RF, optical links to come
- Distributed across the globe for largely continuous coverage
- Can talk to two relays at a time
- Future demands
  - Robotic missions: 17 Mbps return
  - Crewed: 20 Mbps / 150 Mbps



Mars Relay Services

- Space Internetworking
- Networking Time

- In-situ tracking
- In-site navigation

- End-to-end file transfer
- End-to-end messaging
- End-to-end space packet service

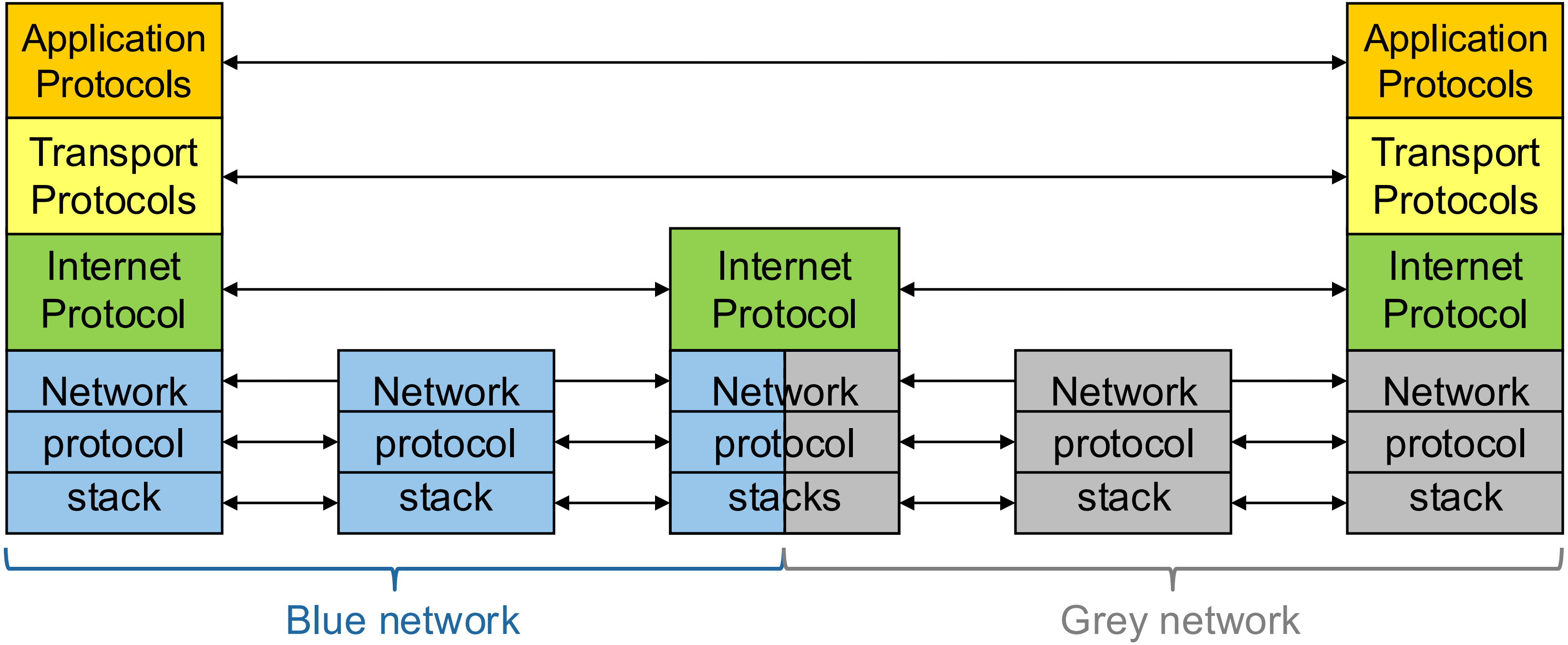
- Complemented by arbitrary local services on Mars
- Real-time rover / robot coordination, sensing, voice, video, …

(Inter)networking on Earth

- Has emerged from a niche into a global utility, transforming many aspects of life
- The Internet as a common infrastructure
  - Is getting “everywhere”
  - Mobile networks (not just) for mobile users
  - Satellite networks as backup and where terrestrial technologies don’t reach
- Formerly disjoint services run over the Internet
  - Telephony, television / streaming, messaging, …
- Underlying (link layer / networking) technologies conquer new areas
  - Vehicles, aircraft, factories, …
- A concept for space?

A closer look: a network of networks

Overlay providing common addressing and best-effort packet delivery service



Internet design assumptions and implications

- Networks can be heterogeneous: IP can run over pretty much everything
  - Variable data rates, reliability (~ packet losses), distances (~ latency), …

But:

- Still, they shouldn’t be too heterogeneous
- Latency matters because of protocol interactivity: < 1s, better < 100ms
- Losses impact performance (retransmissions, congestion control)
- Link disruptions impact packet forwarding (losses)

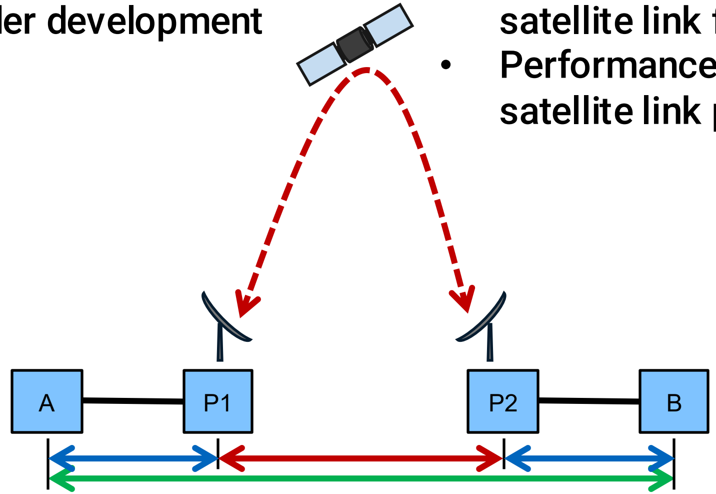
Stretching the Internet into space

Case 1: LEO satellite example: Starlink

- Latency variations, loss bursts, and rate changes impact congestion control
- Resulting in lower throughput
- Dedicated algorithms under development

Case 2: GEO satellites for Internet access

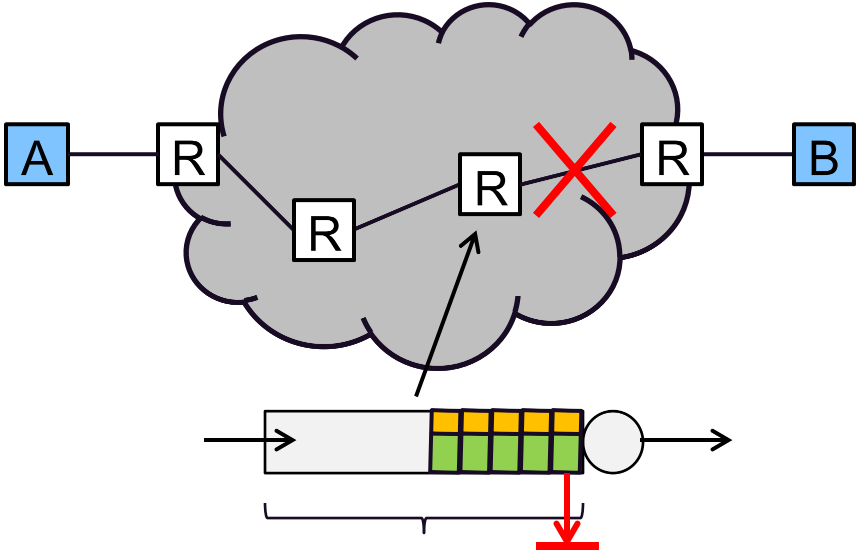
- Long delays (> 250ms) lead to poor protocol and application performance
- Engineering solutions to isolate the “special” satellite link from the rest of the path
- Performance enhancing proxies to cope with satellite link peculiarities



Beyond Earth orbits?

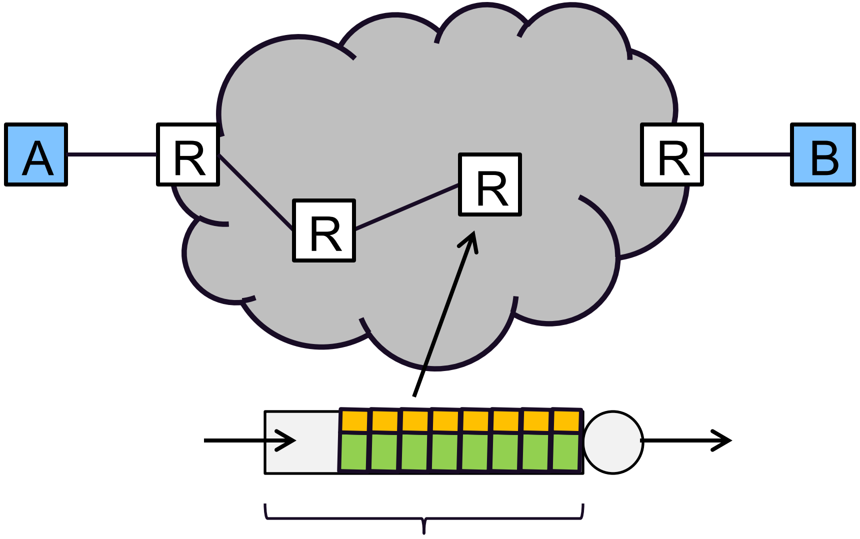
Issues in deep space: delay and intermittent connectivity

Regular Internet operation



Queuing time: 1ms … 1s
Queue capacity: O (MB)

Deep space need: disconnection tolerance



Queuing time: 1ms … 1s … 1h … 1d …
Queue capacity: O (GB – TB)

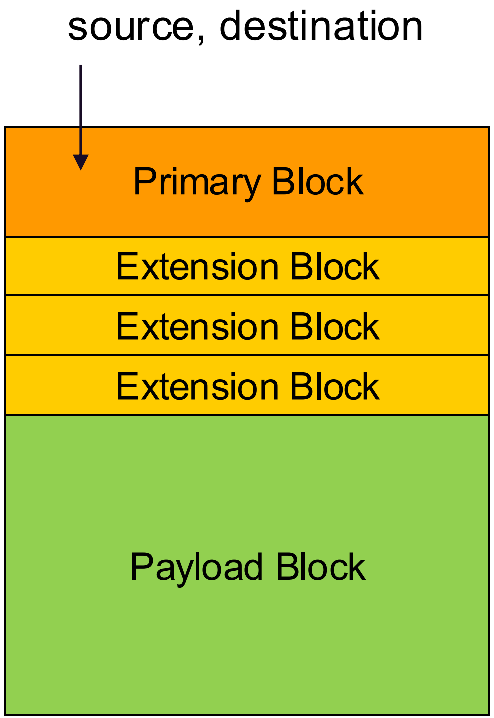
Deep space internetworking – two approaches

- A dedicated networking architecture for the Interplanetary Internet: Delay-tolerant Networking (DTN) Architecture
  - Since the late 1990s / early 2000s
  - IETF DTN WG, CCSDS

- An incremental step to adjusting Internet protocol behavior
  - Fix data, control, and management plane behavior (endpoints, routers, etc.)
  - Adjust supportive services (such as DNS)
  - IETF TIPTOP WG

DTN Architecture + Bundle Protocol [RFC 4838, RFC 9171]

- Principled support for high-latency, disconnected networks
- Asynchronous communication: think "email"
  - Delays may be too long for interactive protocols
  - Avoid handshakes, name lookups, tight feedback loops
- Use large messages instead of small packets
  - Application Data Units (ADUs) of arbitrary size
  - Self-contained and semantically meaningful
  - Message expiration time for garbage collection
- Disruption-tolerant store-and-forward networking
  - Allow storing messages for an extended period of time
  - Hop-by-hop reliability instead of end-to-end
  - Buffer management for congestion control
  - Routing in space time



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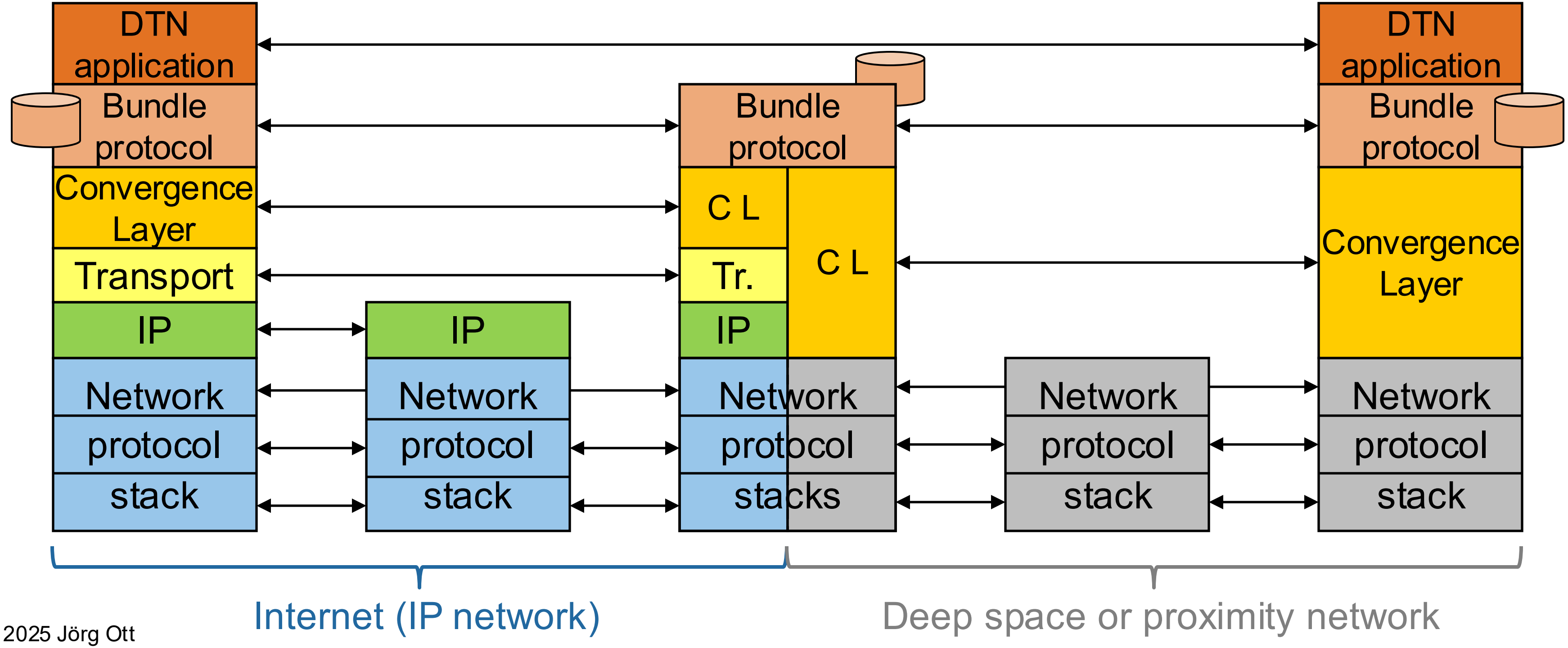
Another network of networks

Overlay providing common addressing and asynchronous messaging



Taking IP To Other Planets (TIPTOP)

- Basic assumption: the Internet protocols are basically fine
  - Proven to work in diverse environments
  - Implemented for many platforms across all scales: from tiny to monster devices
  - 40+ years of operational experience and continuous engineering

- Modern (= recent) protocols overcome past limitations: most notably QUIC
  - New secure transport protocol (not just) for the web
  - Reduced overhead and fewer interactions may allow stretching deeper into space

- Tweak protocols and implementations to fit deep space needs
  - Overcome issues arising from high latency
  - Cope with connectivity disruptions

Focus Areas

- Specifications and standards, architectures and protocols
  - Mars communication architecture, Bundle protocol.
- Performance evaluation
- Link layer properties and constraints
- Mission-specific data demands
- Tools for modeling and simulation / emulation

What We Will Do in The Seminar

- Read and analyze papers, standards and specifications
- Write a technical paper
  - Synthesis / comparison / pro-con discussion
- Present your findings in the class
- Review two peer papers
- Note: The deliverables are still subject to change

- Encouraged to explore own ideas (within scope)

Registration and Next Steps

- Registration using the Matching System

  🛰️ 18.07.2025 – 22.07.2025

- In case of acceptance
  - We will contact you between 05.08.2025 and 31.08.2025 with more information
  - Course deregistration possible until 30.09.2025
  - We will register you for the course in TUMOnline and Moodle beginning of October

Thank you for attending!

Questions?

Feel free to contact us!

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