# Solar System Internet

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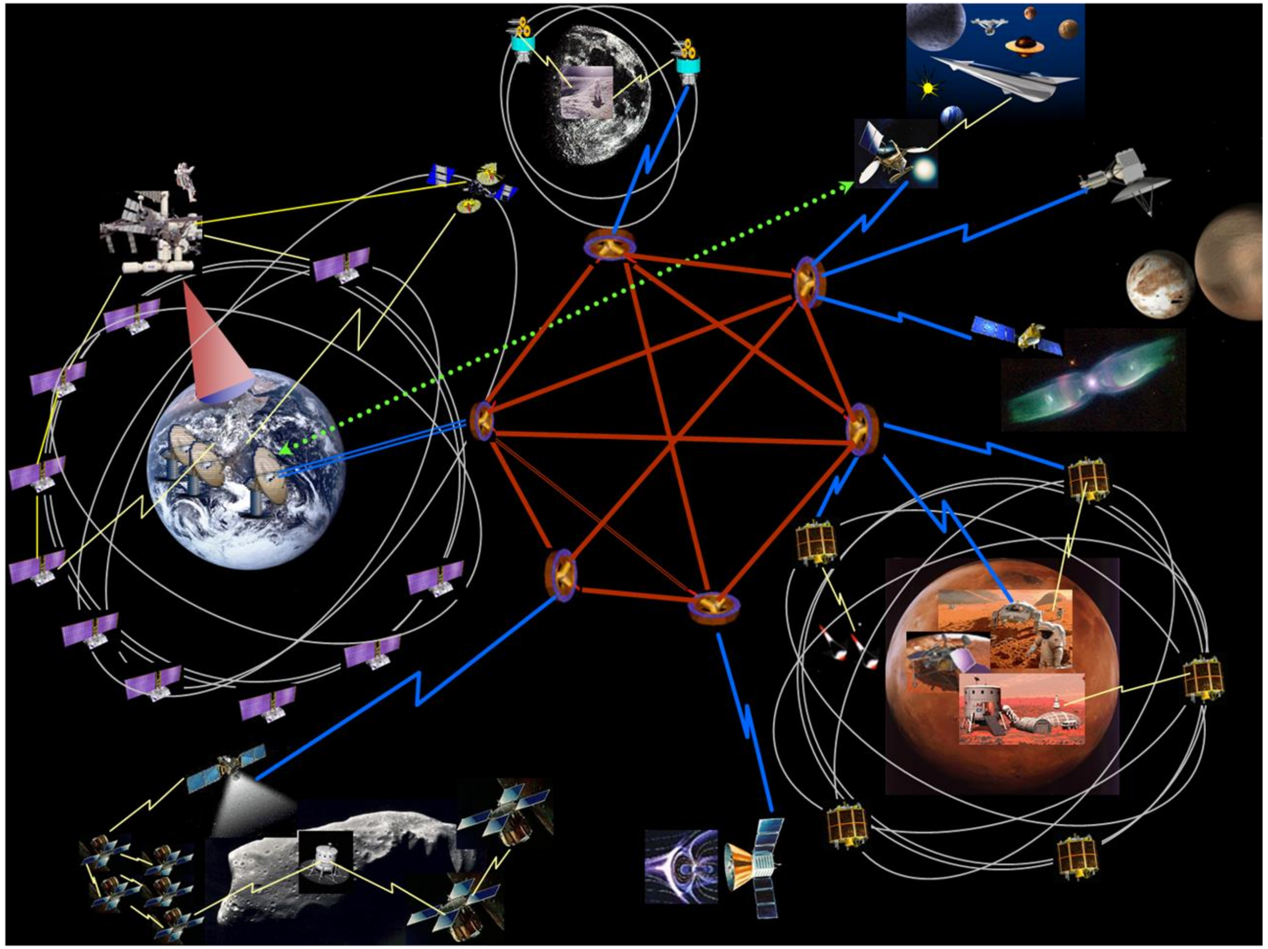
This work was done as a private venture and not in the author's capacity as an employee of the Jet Propulsion Laboratory, California Institute of Technology.

# Overview

- What is the Solar System Internet?
- Why is it needed?
- How will it work?
- When is it going to happen?
- Who is going to build it?



# What…

…is the Solar System Internet?

# It’s like the Internet, but for outer space.

- We already communicate with spacecraft all over the Solar System.
- But all of that communication is intensively managed, at high operational cost.
- A “network” architecture just automates most of the tasks of operating a network: session initiation and termination, routing, multiplexing, congestion control, retransmission of lost data.
- This automation reduces costs, enabling connectivity to scale up.
- This improves cross support, increasing data return and enabling quick recovery from connection failures.

# It’s built on ***Delay-Tolerant Networking***.

- The Internet protocols work great on Earth.
- But we can’t simply extend the terrestrial Internet to other planets by, for example, putting commercial Internet routers on spacecraft.

# Why…

…is it needed?

# Why not just launch commercial routers?

- Communicating entities in space – spacecraft, rovers, habitats – are very far from Earth and (often) from one another.
  - Distance from Earth to Mars varies from 3 light minutes to 22 light minutes.
- Communicating entities in space are often not in continuous contact.
  - A planetary orbiter is periodically on the other side of the planet.
  - Spacecraft may be unable to communicate while acquiring science data.
- So the total time to obtain information from a space entity may be very long and highly variable.
- Many core Internet protocols fail under those conditions.

# Problems with TCP

- TCP acknowledgments may not arrive when expected. This looks like data loss.
- Retransmission is end-to-end, even if data have successfully reached a router local to the destination.
- TCP interprets data loss as congestion, reducing transmission rate. Only successful acknowledgments – each one a potentially long round trip – bring the transmission rate back up. So transmission is slow.
- So TCP is poor for space communications, and many other Internet protocols (BGP, FTP, SMTP, POP, IMAP, SNMP, etc.) rely on TCP.

# Problems with Client/Server

- Much of the Internet, including the World-Wide Web (HTTP), is built on the client/server model: an entity that requires information sends a request to a server, and the server sends the information back.
- This is great when round-trips are always brief.
- But when round-trip times can vary from minutes to days, the answer may arrive only long after it is no longer needed.
    - It is much better to subscribe to information long before it is needed, receive it in advance, and store it locally.

# Delay-Tolerant Networking

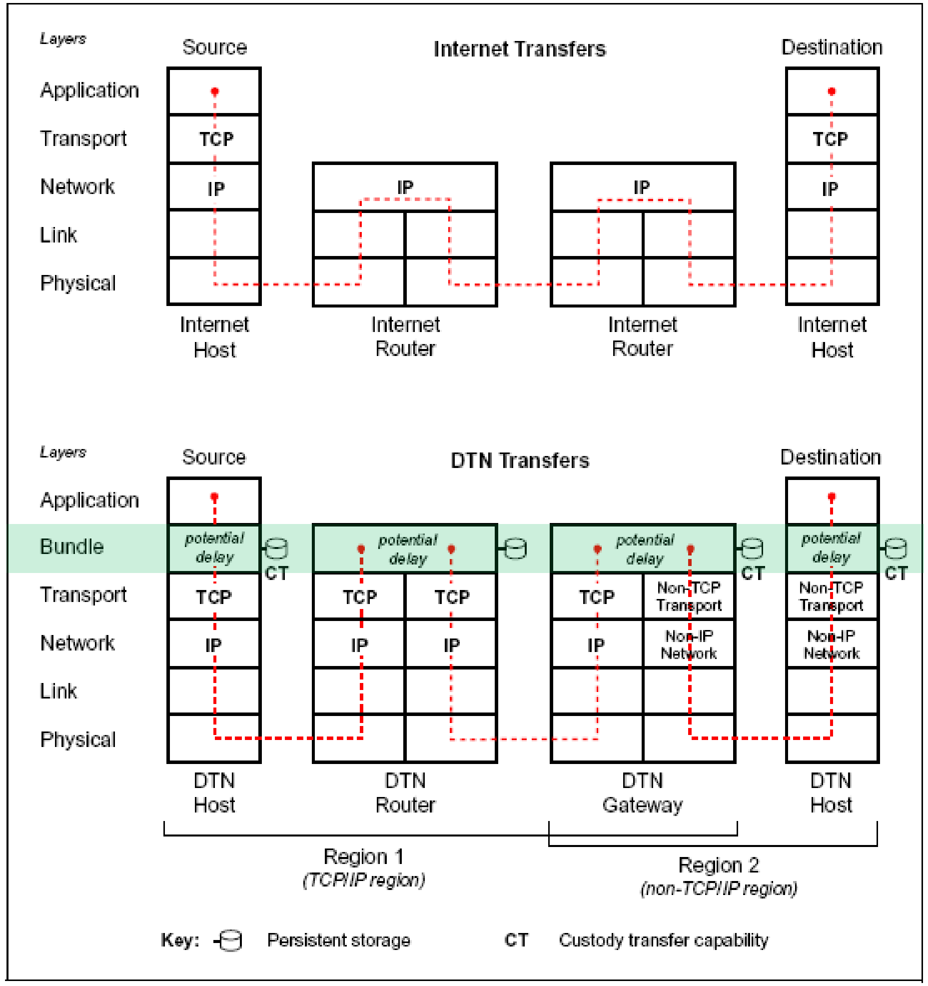
- Because the Internet architecture itself is not suitable, we need a new architecture for the Solar System Internet.
- This architecture is called delay-tolerant networking.
  - Large and highly variable round-trip times are expected.
  - Data are published to subscribers as soon as they are available.
  - Lost data are retransmitted within the network rather than end-to-end.
  - Loss of link results in data retention until connectivity is restored, is not interpreted as a network partition.

# How…

…will it work?

# Bundle Protocol

- BP is the network-layer protocol of the DTN architecture.
- Like Internet Protocol (IP):
  - Overlay, interconnecting subnets.
- But unlike IP:
  - Link outage is assumed transient, not a network partition.
  - Data that can't immediately be forwarded are retained, not discarded.

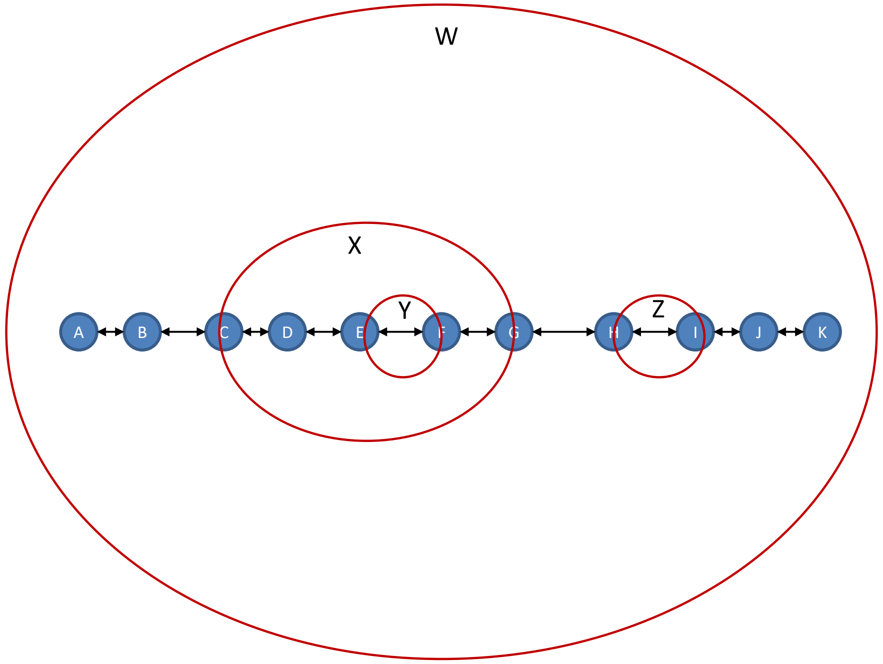


# Licklider Transmission Protocol

- LTP is the deep-space ARQ protocol of DTN architecture.
- Like TCP:
  - Positive and negative acks, timeout-driven retransmission.
- Unlike TCP:
  - Retransmits between routers, not end-to-end.
  - Multiple concurrent transmission sessions.

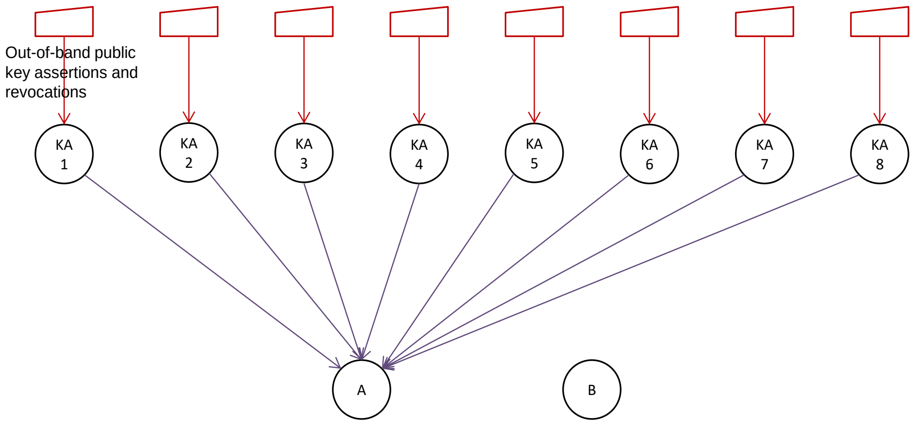
# Bundle Security Protocol

- Like Internet security protocols, provides Authentication, Integrity, and Confidentiality.
- Unlike Internet security protocols, it is built directly into the network protocol as an extension, not a separate layer.
  - Bundles are protected at rest (while awaiting transmission) as well as in transit.
  - Encapsulation for cross-domain.



# Delay-Tolerant Key Administration

- Like Internet PKI, DTKA provides public key information to network nodes.
- Unlike Internet PKI, public keys are published in advance.
    - Key distribution is delay-tolerant.
    - Distributed consensus among key authority nodes ensures authenticity of key information.




Only blocks with the same hash will be reassembled into the bulletin, so if any KA is inadvertently out of agreement its bulletin will be ignored.

# Contact Graphs

- Spacecraft operate according to mission plans, so episodes of connectivity – contacts – are known in advance:
  - Sending and receiving nodes.
  - Start and end times.
  - Displacements between nodes (one-way light time).
  - Transmission data rates.
- Contact plans are powerful:
  - Basis for routing, i.e., next-hop transmission selection on end-to-end path.
  - Basis for rate control.
  - Enable bundle delivery time estimation.
  - Enable bundle round-trip time estimation.

# Congestion Control

- Contact plans can be used to forecast estimated congestion – aggregate data reception rates in excess of aggregate transmission rates over time.
  - Given a congestion forecast, network management can revise contact plans in time to prevent congestion.
- Bundle round-trip time estimation, computed from contact plans, enables computation of accurate bundle lifetime limits.
  - Bundle time-to-live expiration causes bundles to be deleted from retention buffers, relieving congestion.

# Delay-tolerant Applications

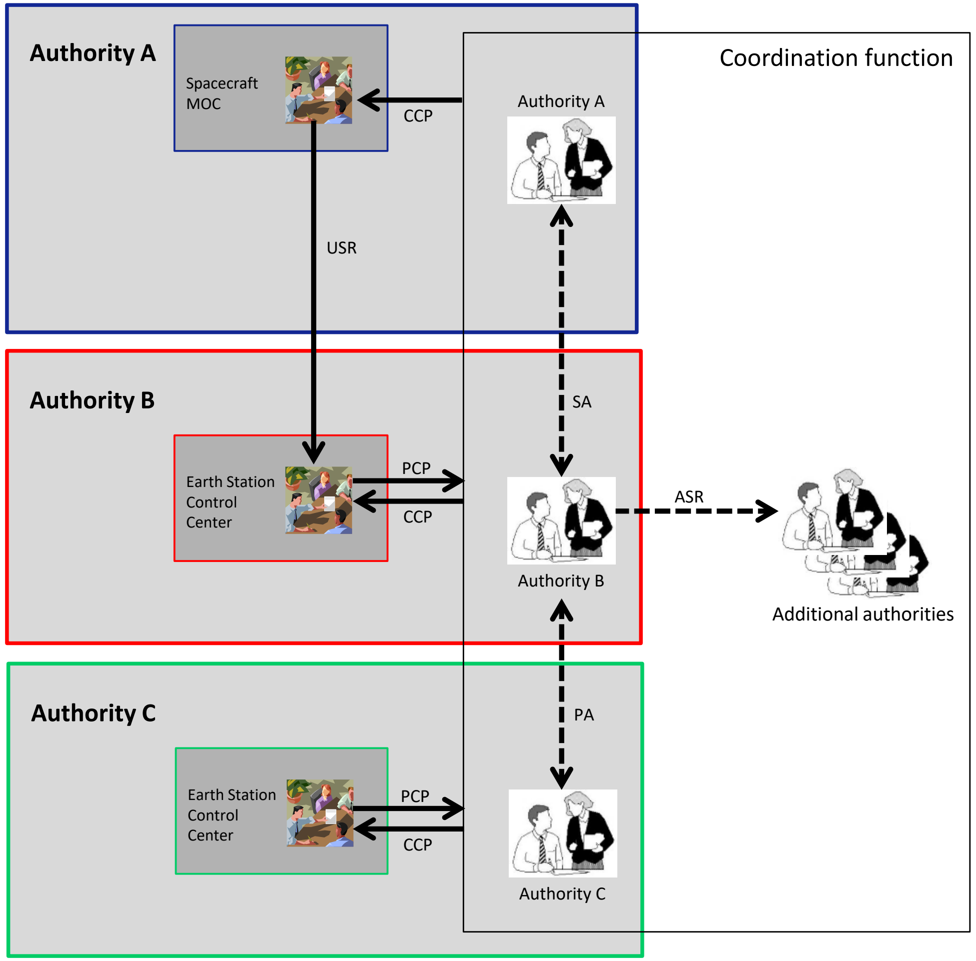
- CCSDS File Delivery Protocol (CFDP)
  - Using BP as its Unitdata Transfer layer.
- CCSDS Asynchronous Message Service (AMS)
  - Fine-grained control over message subscription and publication.
- Bundle Streaming Service
  - Delay-tolerant mechanisms for streaming telemetry, audio, and video over a DTN-based network.
- Last-hop Service
  - A disabled network node may still be able to decode link-layer commands from a neighboring spacecraft, which receives command packages via DTN.

# New protocols at lower layers

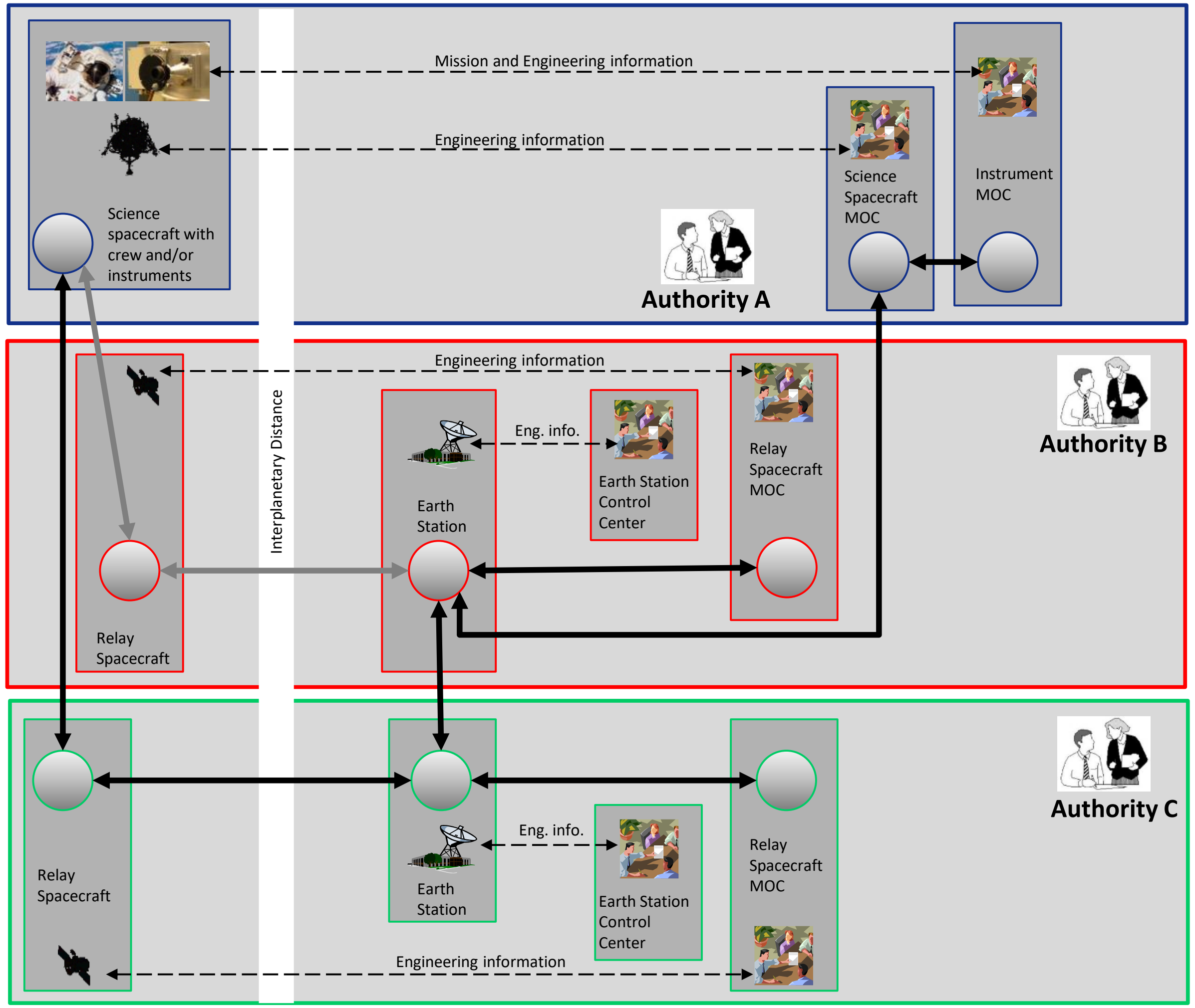
- CCSDS Unified Space Data Link Protocol (USLP)
  - Combines key features of the Telemetry (TM), Telecommand (TC), and Advanced Orbiting Systems (AOS) link-layer protocols.
  - Simplifies network configuration and management.
  - Support symmetric communication relationships among entities in space.
    - No longer just forward uplink from ground and return downlink from spacecraft.
- High-capacity physical-layer technologies
  - Ka-band radios
  - Free-space optical transmission

# SSI Organizational Structures

- USR: User Schedule Request
- PCP: Provider Contact Plan
- CCP: Composite Contact Plan
- SA: Service Agreement
- ASR: Authority Schedule Request
- PA: Peering agreement



# Interoperation



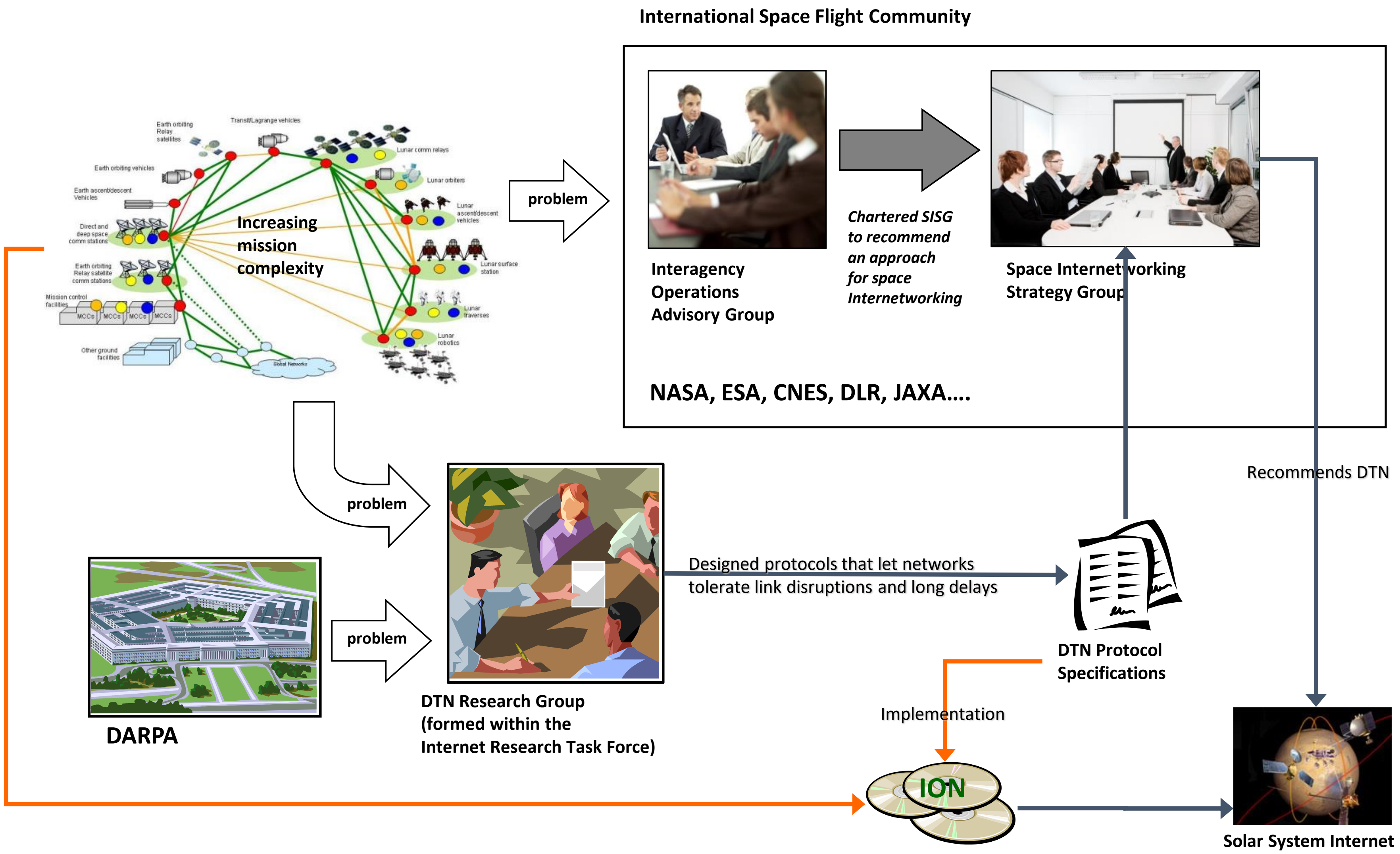
# Deployment

- Standards have been published by CCSDSD
- …and software implementations exist,
- …so DTN can be deployed on science and exploration missions,
- …so upon mission completion these spacecraft can be repurposed as DTN routers.
- Small marginal cost to deploy the Solar System Internet.

# When…

…is it going to happen?

# How we got here



# Timeline

- Specifications for DTN protocols were published starting in 2005.
- Version 1 of Interplanetary Overlay Network (ION) space flight implementation of DTN protocols was announced later that year.
- First demonstration of DTN on a spacecraft in deep space was the Deep Impact Network experiment in 2008.
- Standards now published by CCSDS, starting in 2015.
  - Standardization for the Internet, in IETF, is also in progress.

# What now?

- ION was deployed aboard the International Space Station in May of 2016. Multiple ISS science experiment payloads are planning to use the DTN communication service.
- Work is under way to integrate ION into NASA flight radios.
- DTN is being evaluated by the Korean national space program for possible use in a lunar mission.
- Many other evaluation and development initiatives in progress worldwide.

# Who…

…is going to build it?

# You are.

- National space agencies will do the initial deployment and establish the organizational framework.
- Commercial enterprises, venturing into space to exploit resources in Earth orbit, on the moon, and on asteroids, will leverage that work to create an interplanetary communication fabric.
- A lot like the Internet.

# Questions?