Challenges in Deep Space Networking

Rick Taylor, Aalyria

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Introduction

This talk is intended for a broad audience who are not necessarily familiar with the current engineering efforts in deep space networking, or the activities happening in the IETF.

I will provide an overview of the following:

- A scoping definition of “deep space” as compared to “near space”, outlining what makes the deep space environment fundamentally different from the terrestrial environment
- A view of the long term vision for deep space networking, and the two major approaches being taken in the IETF and elsewhere.
- An incomplete list of open research topics

Disclaimer

- All this content is my personal opinion
- All lists are incomplete
- All assertions can (and should) be challenged
- There is just so much we don’t know how to do yet!

What do I not mean by ‘Deep Space Networking’

In practical terms, it takes about 1.3 seconds for light to travel the distance between the Earth and the Moon, and so communicating with devices in Earth orbit can be considered a traditional wireless networking problem.

There are obvious complexities introduced by the orbital mechanics of satellite constellations, but they can be considered a subclass of the problems related to building networks of moving nodes.

The same applies to establishing communication with the Earth-facing side of the Moon, either direct or via relays, as demonstrated by the lunar programmes of the 1960’s and 70’s.

What do I mean by ‘Deep Space Networking’

For the purposes of this presentation, I shall define Deep Space Networking as:

Interconnecting nodes over distances where their position and motion causes outages and transmission delays unlike those commonly found on Earth

Examples include:

- Communication with the far side of the Moon
- Communication with the Martian surface
- Communication with missions further out into the Solar system

The Challenges

There are several major challenges:

1. Space is **BIG**:
   - The distances are measured in AU, and the speed of light really matters
   - General Relativity has a noticeable effect
2. Everything in space moves and rotates:
   - Planetary bodies get in the way
   - Nodes on planet surfaces rotate with the parent body
   - Spacecraft move and spin
3. Power consumption is a critical consideration
   - Most of space is too dark for solar, so spacecraft are dependent on their own energy reserves for the lifetime of their missions
4. Human access to network devices is almost impossible
   - Automation, autonomy, and fail-safe behaviour is required everywhere

The Solar System Internet (SSI)

We have been able to establish line of sight communication circuits between Earth and individual spacecraft for decades, but that approach does not scale.

The long-term vision of those concerned with space exploration, driven by the Consultative Committee for Space Data Systems, a UN body, is for an Internet-style pervasive packet-switched network spanning the solar system.

Although this will take decades to build out, work has already started, and I shall outline some of the challenges that require further research.

Two approaches

There are two main approaches to the problem:

1. Because of the distances involved and the cost of launching spacecraft, the SSI should be considered a *sparse* network. Therefore the approach is to build a network built on a "Store, Carry, Forward" principle, to handle the absence of persistent end-to-end connectivity.
2. The Internet is an undeniable success, and economies of scale point to reusing the well-understood principles of IP networking, tuned for the distances involved, assuming that the SSI will eventually be *dense* enough to provide end-to-end connectivity.

Both approaches are viable, given their underlying assumptions, and are not mutually exclusive.

I assert that even when the inner solar system is populated sufficiently to act as a dense IP network, there will always be a sparse outer frontier.

DTN with Bundle Protocol

In a Store, Carry, Forward network, in order to achieve end-to-end communication, it must be possible for messages to linger at intermediate nodes until the next transmission opportunity occurs.

In order the achieve this the IETF DTN Working Group has standardised the Bundle Protocol (RFC9171) that defines a general-purpose encapsulation of an application data unit, with all associated metadata, suitable for transmission in such a Store, Carry, Forward manner.

Work is ongoing on naming and addressing of bundles and nodes, adding encryption and authentication to bundles, and the control and management plane protocols to operate such bundle networks.

Taking IP To Other Planets (TIPTOP)

The IETF TIPTOP Working Group is working on a gap analysis of the current IP protocol suite, examining where the extreme distances and disruptions of deep space require tuning of the existing protocols.

The working group has only just formed, and is currently focussing on profiling QUIC for links with long latency.

Open General Research Topics

There are many open areas of research to address the challenges of deep space networking, and both the DTN and TIPTOP working group support the SPACE-RG as a suitable venue for such research, prior to possible standardisation in the IETF.

There is an excellent breakdown of the general research areas in the SPACE-RG materials at: https://github.com/irtf-spacerg/spacerg-materials/blob/main/charter/charter.md which I'm not going to repeat.

Some Research Topics in Deep Space Networking

- Because of the noticeable effects of General Relativity, how do we manage time?
  - Can protocols survive the absence of a consistent “network time”?
  - How does that affect cryptographic key lifetimes and associated management?
  - Do we need new NTP-like protocols that include General Relativity?
- Because of the critical power constraints, are wireless links used efficiently?
  - Can we do smarter things at L1/L2?
  - Can we design protocols that are less “chatty” and therefore burn fewer Watts?
    - Do we even understand the power consumption profiles of protocols?
- Because of the lack of hands-on servicing, do we understand how to imbue devices with autonomy?
  - Can we be flexible AND fail-safe?
    - NB: There is work in the DTN WG on this topic, but the proposals are incompatible with NETCONF, is that ok?
  - Is there a role for ‘Agentic AI’ here, or is that just a hype-train?
- Because the SSI will not be built and operated by a single agency, how do multiple bodies collaborate?
  - How do different providers ‘peer’, and what does that peering involve?
  - How is authentication and identity managed, or are the current best practices for the terrestrial Internet sufficient?
  - How will DNS work across interplanetary distances?
- Because of the distances involved, and the massive round-trip times, how will end-users be affected?
  - Does the pervasive HTTP/REST API paradigm still work with 40+ minute delays?
  - What will the 22nd Century version of Snapchat be?

Conclusion

There are a lot of exciting developments in deep space networking happening in the next decades, and the open list of research topics will continue to grow.

My hope is that the SPACE-RG will become a critical meeting point for the research community and the wider engineering community involved.

But as we start to find the gaps in our knowledge, if you are interested in any of these subjects - ask!

There are a number of world experts in this field involved with the group, and if they don’t know the answer to your question, then you’ve just discovered another research topic.

Thank you