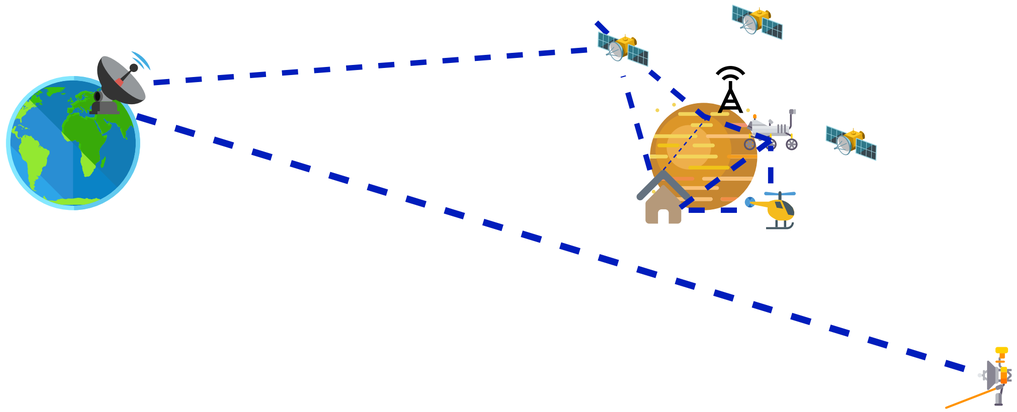

Internet Protocol Stack in Deep Space: Architecture and Simulation Results

76th International Astronautical Congress (IAC 2025)
Sydney, Australia, 29 Sep-3 Oct 2025

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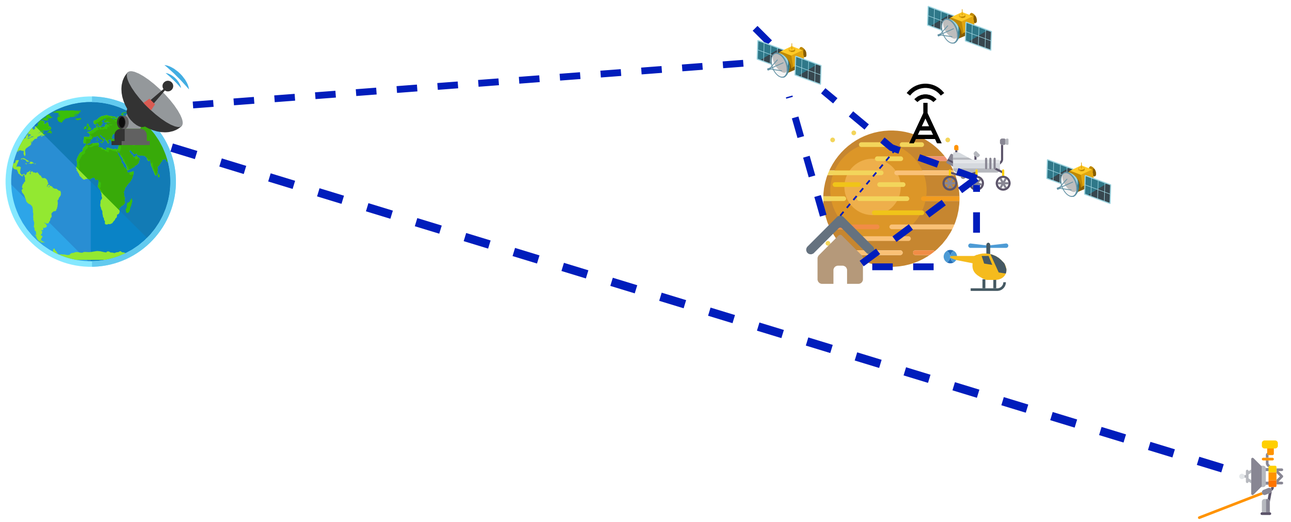
Me

- Internet engineer for 30+ years
- Developed protocols (wrote 17 RFC, wg chair of many IETF wg, IAB member)
- President of Viagenie, consulting for providers, large entreprises, space agencies and manufacturers
- Space related:
  - Involved in space comm/networking since early 2000.
  - IETF delay tolerant networking(dtn) wg co-chair for ~10 years.
  - Member of Interplanetary Network SIG(IPNSIG) Architecture WG and Projects WG
  - Lead of the IOAG LunaNet networking governance working group
  - Designed, implemented and managed the Space Assigned Number Authority(SANA)
  - Instigated the Deep space IP initiative and proposed the IETF tiptop (Taking IP to Other Planets) working group, where I'm technical advisor and delegate

Moon Comms Deployment

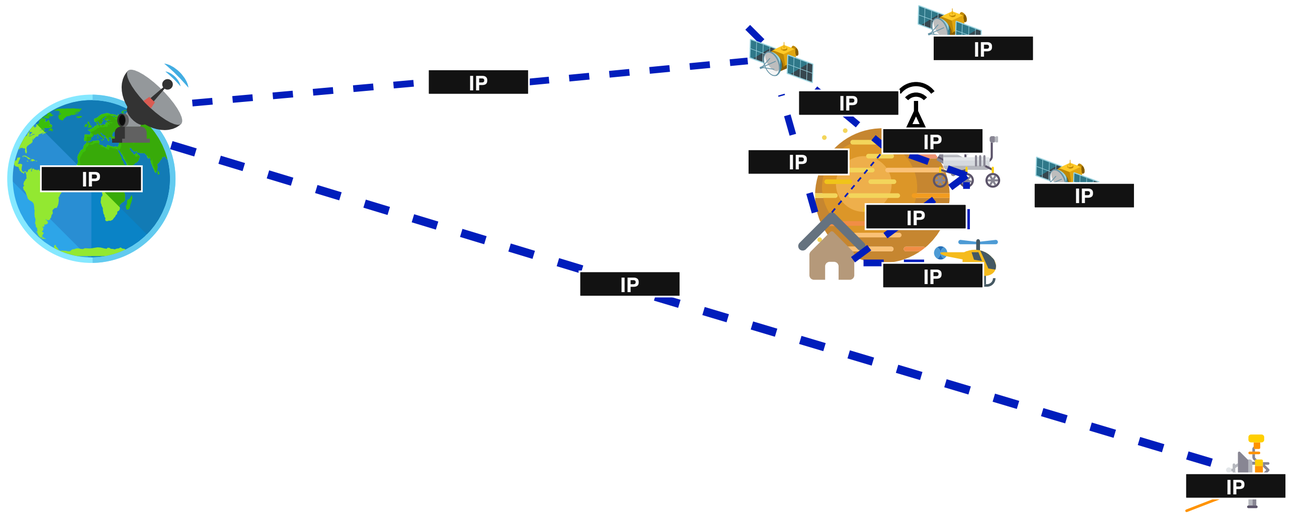
- Communication/relay orbiters
- Surface assets: habitats, rovers, ...
- Link layers:
  - Surface and orbital: 3GPP (5G/6G) and WIFI
  - Deep space/Orbital: CCSDS
- Earth-Moon delay < 2s



Moon Comms Deployment

With Networking Layer

- All links carry Internet Protocol (IP)
  - Only IP runs over 3GPP and WIFI
- Therefore creating a single layer 3 network end to end
- Why?
  - multiple providers and multiple users/customers
  - sharing common infrastructure
  - Enabling end to end reachability from any to any, using the network



- Note 1: Spacecraft on-board is also an IP network
- Note 2: some relays such as ESA Lunar Pathfinder are forwarding at layer 2, so carries IP

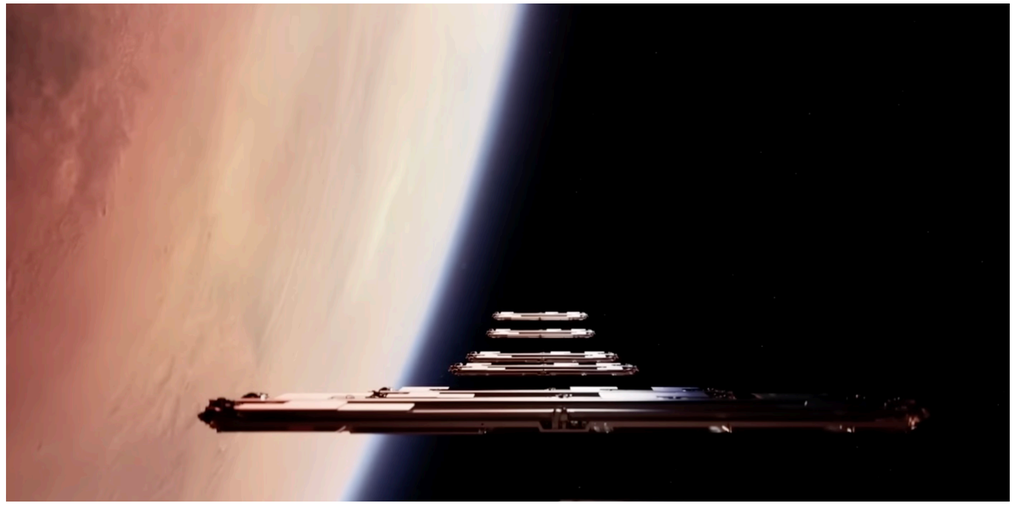
* The Future Lunar Communications Architecture, Report of the Interagency Operations Advisory Group", January 2022
** LunaNet Interoperability Specification, NASA, February 2025

Mars Comms Deployment

- Same architecture for Mars*
- but different deployment pace

- Earth-Mars delay: 4-22 minutes

* Blue Origin Mars Telecommunications Orbiter , August 2025



* SpaceX update, Elon Musk 29-05-2025

* The Future Mars Communications Architecture, Report of the Interagency Operations Advisory Group", February 2022

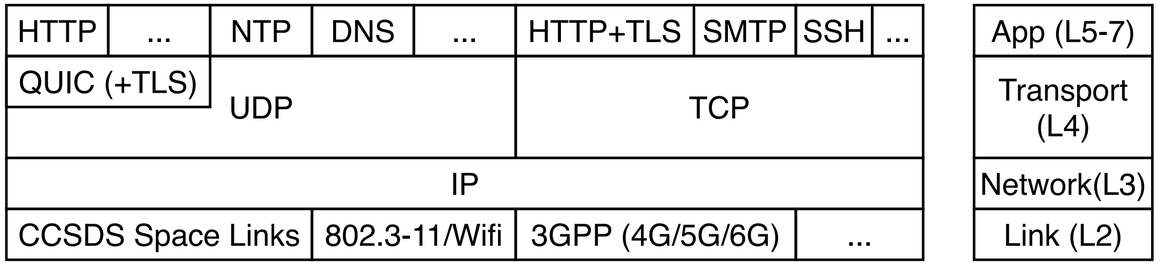
Main Networking Challenges in Deep Space

- Compared to Internet well-connected low delay, space has:
  - Long delays
    - "Simpler to fix": expect to take longer... adjust timers.
    - But cannot expect immediate reaction to events/no fast closed loop
  - Intermittent communications (orbiters going on the other side)
    - "More complicated": from the end to end point of view, the round-trip time (RTT) is large, but more importantly very variable, with jumps due to orbiters going off line of sight
    - A mechanism assuming a relatively stable RTT will just fail.
      - BTW, RTT is not stable on Internet: congestion happens, then recovery kicks in. But immediate/fast reaction is possible. Not in space

- * Space communications has many other challenges, but handled at lower layers
- * more information in draft-ietf-tiptop-usecase

IP Network Layer

- Provides end-to-end(e2e) communication
- Over any link layer below (IP over anything)
- Any length or size of network
- Rely on upper layer (transport) for e2e reliability
  - Transport handles: loss, duplication, reordering, flow control and congestion control
  - And e2e security at transport level
  - Both frees up the application to care about those
- Complexity handled at endpoints, intermediate nodes are simple, therefore fast and hardware accelerated, energy efficient, low memory requirements, no encryption to consume CPU and energy.



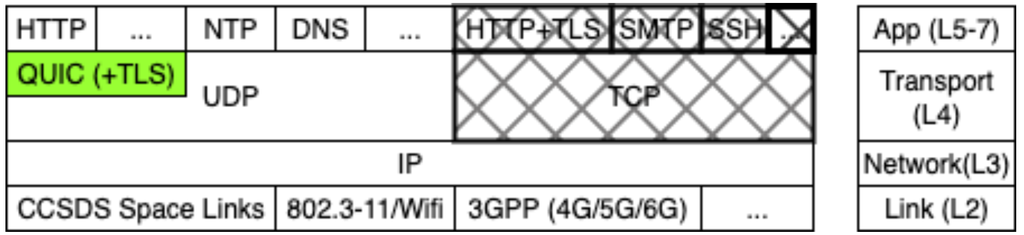
What needs to be done on IP suite for Deep Space?

- IP and UDP (and HTTP) have no notion of time. Nothing to adapt.

A. For forwarding devices (like orbiters or space edge) facing intermittent links:
    - Buffer packets temporarily (instead of dropping them) when no route to destination
        - Not needed for:
            - surface or 5-6G/Wifi forwarders/routers
            - Layer 2 orbiters/gateways (if they don't know about IP, just forward based on CCSDS link layers, like Mars orbiters currently)
            - Non-forwarding end nodes

B. To deliver end to end reliability, configure transport (QUIC) based on a deep space profile
    - Right set of values for timers
    - Intermittence is not directly seen by transport: it is just long and variable delays
    - Do not rely on typical RTT for internal calculations

C. Applications/Tools/...: asynchronous design, adjust timers appropriately

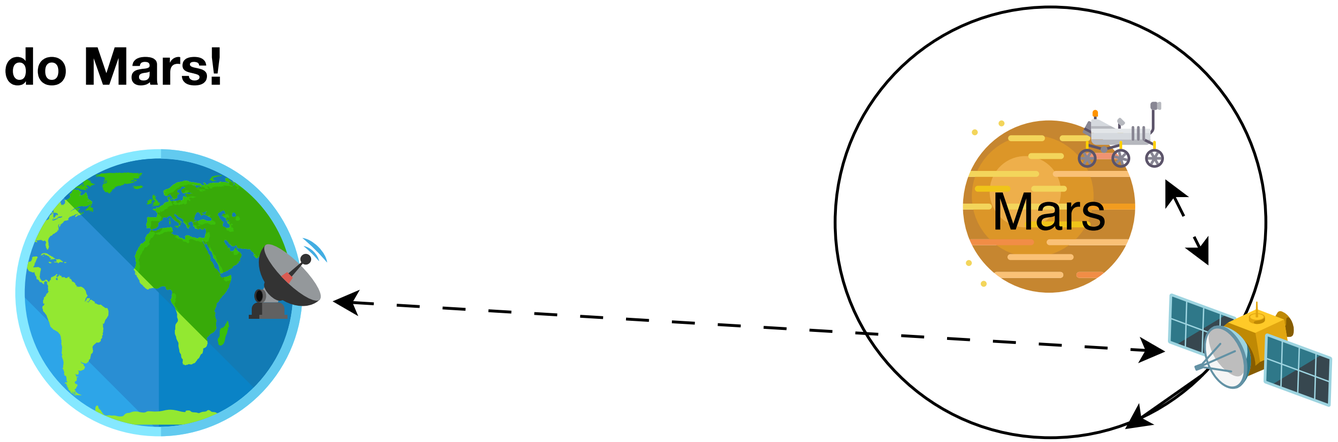


- TCP not suitable for space
- And everything above TCP
- Use profiled QUIC instead

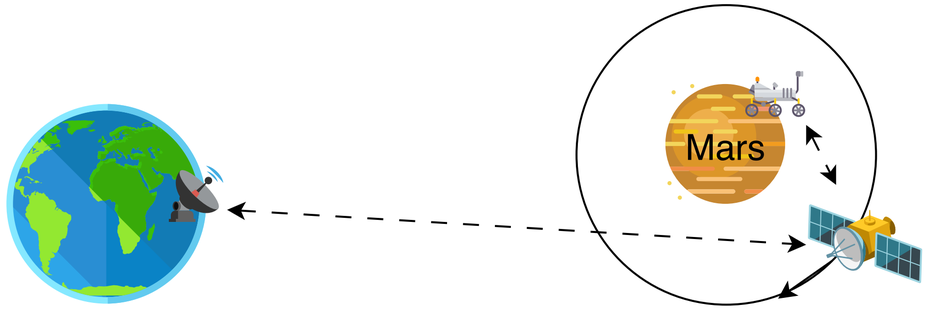
Does IP work in Deep Space?

Let's put it to test!

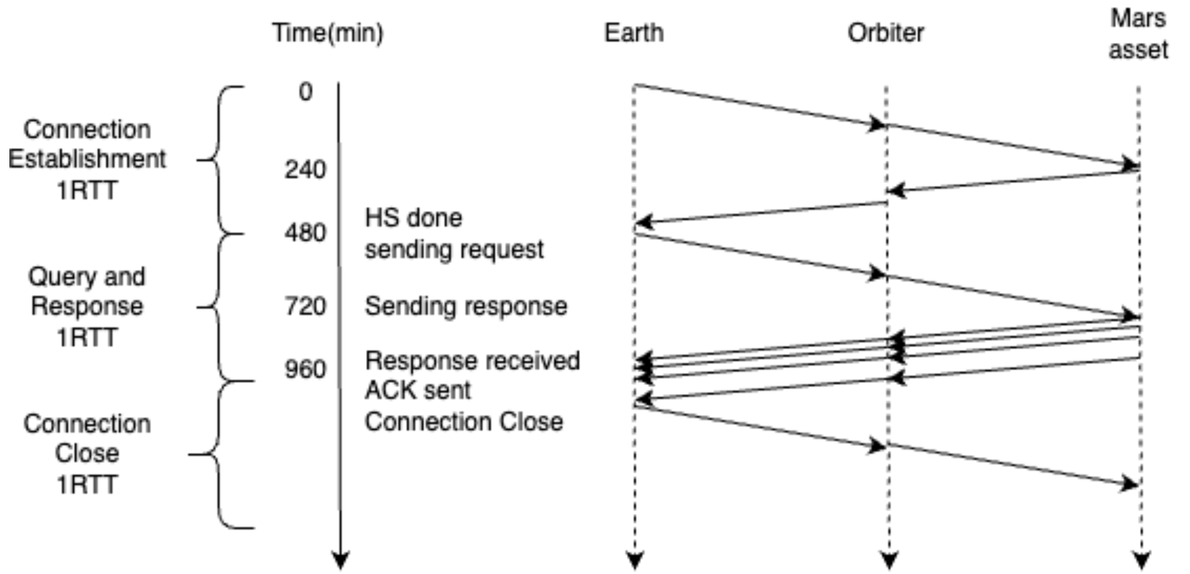
Moon: 1.5 seconds. Too easy ;-). Let's do Mars!



Earth to Mars via Orbiter



- Simulation: HTTP/QUIC request and response
- 4 min (240s) one-way delay (Mars and Earth nearest)
  - Side note: <270s max for tc netem delay before 2024-02 fix
- Direct Earth node - Mars orbiter - Mars asset: no intermittence
- HS = 1RTT Handshake
- Connection close: not needed, can keep connection opened "forever" for additional requests
- Two different QUIC implementations used



Client Wireshark

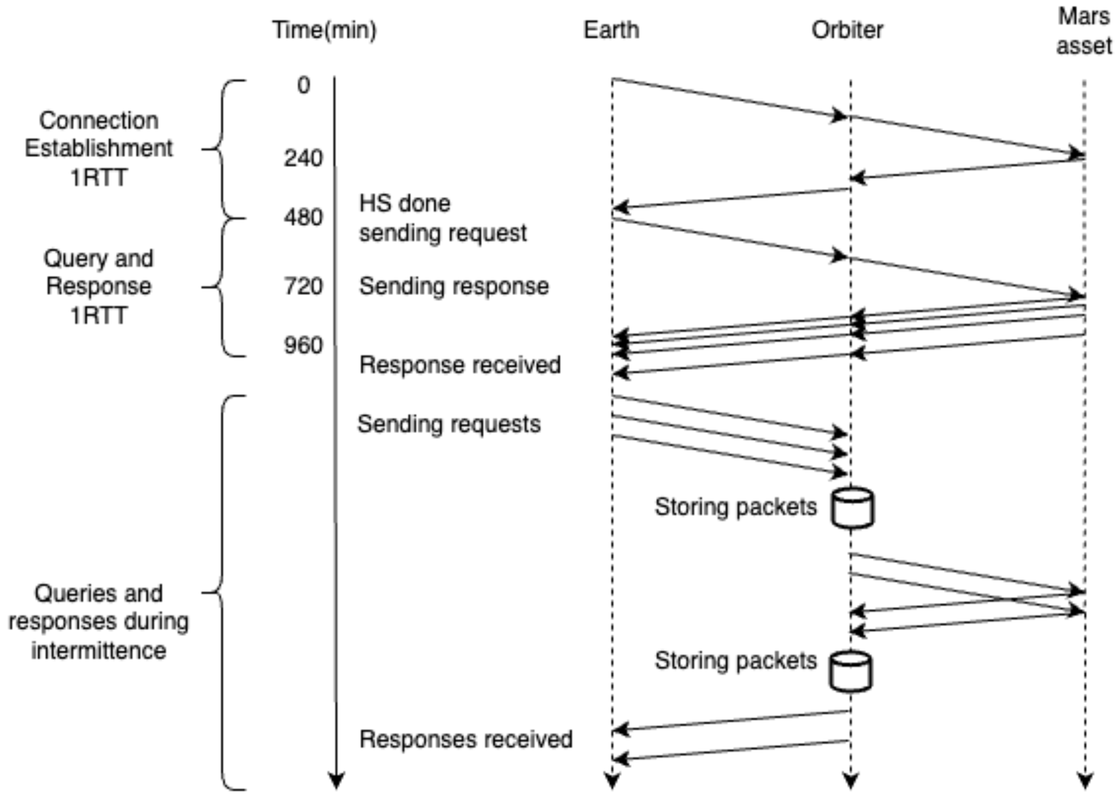
No.	Time	Source	Destination	Protoc	Length	Info
1	0.000000	192.168.40.1	192.168.42.1	QUIC	1242	Initial, DCID=ba7bb2be15d544e9aa76900070e41a9bacaa826e, SCID=dbd14607fed99229, PKN: 0, CRYPTO, PADDING
2	240.763219	192.168.42.1	192.168.40.1	QUIC	1686	Handshake, DCID=dbd14607fed99229, SCID=bc54d768409abe435a4c5c4904abe9788b088cc9, PKN: 2, CRYPTO
3	480.801468	192.168.40.1	192.168.42.1	QUIC	1242	Handshake, DCID=bc54d768409abe435a4c5c4904abe9788b088cc9, SCID=dbd14607fed99229, PKN: 0, ACK, CRYPTO, PADDING
4	480.801600	192.168.40.1	192.168.42.1	QUIC	276	Protected Payload (KP0), DCID=bc54d768409abe435a4c5c4904abe9788b088cc9, PKN: 0, NCI, NCI, NCI, NCI, NCI, NCI, NCI
5	480.801602	192.168.40.1	192.168.42.1	QUIC	100	Protected Payload (KP0), DCID=bc54d768409abe435a4c5c4904abe9788b088cc9, PKN: 1, STREAM(0)
6	721.486731	192.168.42.1	192.168.40.1	QUIC	803	Protected Payload (KP0), DCID=dbd14607fed99229, PKN: 3, ACK, NCI, NCI, NCI, NCI, DONE, CRYPTO, STREAM(0)
7	961.609775	192.168.40.1	192.168.42.1	QUIC	86	Protected Payload (KP0), DCID=bc54d768409abe435a4c5c4904abe9788b088cc9, PKN: 2, ACK
8	961.609810	192.168.40.1	192.168.42.1	QUIC	93	Protected Payload (KP0), DCID=bc54d768409abe435a4c5c4904abe9788b088cc9, PKN: 3, ACK, CC

What about intermittence?

Such as orbiter with blackout periods

Earth to Mars with Intermittence

- IP packets stored during intermittence
- Intermittence: 1h, 2 times
- 4 min. one-way delay
- Send 1 request every 15 minutes
  - 20 times: aka 20 requests, 20 responses



Earth to Mars with Intermittence

Requests every 15 min.

Orbiter-Asset link down. Packet storage.

1	0.000000	192.168.40.1	192.168.42.1	QUIC	1242	Initial, DCID=bfac32299c63c485a3db2566ad9b8a36dd5faa27, SCID=896064ae61744008, PKN: 0, CRYPTO, PADDING
2	240.705935	192.168.42.1	192.168.40.1	QUIC	1380	Protected Payload (KP0), DCID=896064ae61744008
3	480.733715	192.168.40.1	192.168.42.1	QUIC	1242	Initial, DCID=cc5a86d7b7951123, SCID=896064ae61744008, PKN: 1, ACK_ECN
4	480.733733	192.168.40.1	192.168.42.1	QUIC	180	Protected Payload (KP0), DCID=cc5a86d7b7951123
5	480.733735	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
6	480.733736	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
7	721.601456	192.168.42.1	192.168.40.1	QUIC	416	Protected Payload (KP0)
8	721.601456	192.168.42.1	192.168.40.1	QUIC	203	Protected Payload (KP0)
9	961.659318	192.168.40.1	192.168.42.1	QUIC	76	Protected Payload (KP0), DCID=cc5a86d7b7951123
10	961.659340	192.168.40.1	192.168.42.1	QUIC	96	Protected Payload (KP0), DCID=cc5a86d7b7951123
11	1380.733785	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
12	1621.433896	192.168.42.1	192.168.40.1	QUIC	76	Protected Payload (KP0)
13	1621.433897	192.168.42.1	192.168.40.1	QUIC	203	Protected Payload (KP0)
14	2280.842765	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
15	2342.318865	192.168.40.1	192.168.42.1	QUIC	79	Protected Payload (KP0), DCID=cc5a86d7b7951123
16	2521.647591	192.168.42.1	192.168.40.1	QUIC	203	Protected Payload (KP0)
17	3002.520627	192.168.42.1	192.168.40.1	QUIC	79	Protected Payload (KP0)
18	3180.961165	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
19	3242.549809	192.168.40.1	192.168.42.1	QUIC	79	Protected Payload (KP0), DCID=cc5a86d7b7951123
20	3421.709413	192.168.42.1	192.168.40.1	QUIC	203	Protected Payload (KP0)
21	4081.022304	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
22	4142.610331	192.168.40.1	192.168.42.1	QUIC	79	Protected Payload (KP0), DCID=cc5a86d7b7951123
23	4981.097722	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
24	5881.122075	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
25	6781.207992	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
26	7681.127528	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
27	8581.162835	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
28	8614.130449	192.168.42.1	192.168.40.1	QUIC	102	Protected Payload (KP0)
29	8854.144409	192.168.40.1	192.168.42.1	QUIC	78	Protected Payload (KP0), DCID=cc5a86d7b7951123
30	9481.129946	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
31	10381.362734	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
32	11281.370662	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
33	12181.474612	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
34	13081.634629	192.168.40.1	192.168.42.1	QUIC	88	Protected Payload (KP0), DCID=cc5a86d7b7951123
35	13981.768204	192.168.40.1	192.168.42.1	QUIC	89	Protected Payload (KP0), DCID=cc5a86d7b7951123
36	14398.274138	192.168.42.1	192.168.40.1	QUIC	78	Protected Payload (KP0)
37	14398.274139	192.168.42.1	192.168.40.1	QUIC	365	Protected Payload (KP0)
38	14398.274139	192.168.42.1	192.168.40.1	QUIC	364	Protected Payload (KP0)
39	14638.302876	192.168.40.1	192.168.42.1	QUIC	79	Protected Payload (KP0), DCID=cc5a86d7b7951123
40	14881.742836	192.168.40.1	192.168.42.1	QUIC	89	Protected Payload (KP0), DCID=cc5a86d7b7951123
41	15122.532603	192.168.42.1	192.168.40.1	QUIC	204	Protected Payload (KP0)
42	15603.527251	192.168.42.1	192.168.40.1	QUIC	79	Protected Payload (KP0)
43	15781.746285	192.168.40.1	192.168.42.1	QUIC	89	Protected Payload (KP0), DCID=cc5a86d7b7951123
44	15843.428086	192.168.40.1	192.168.42.1	QUIC	81	Protected Payload (KP0), DCID=cc5a86d7b7951123
45	16022.426337	192.168.42.1	192.168.40.1	QUIC	204	Protected Payload (KP0)
46	16503.365773	192.168.42.1	192.168.40.1	QUIC	79	Protected Payload (KP0)
47	16681.808234	192.168.40.1	192.168.42.1	QUIC	89	Protected Payload (KP0), DCID=cc5a86d7b7951123
48	16743.511417	192.168.40.1	192.168.42.1	QUIC	79	Protected Payload (KP0), DCID=cc5a86d7b7951123
49	16922.628931	192.168.42.1	192.168.40.1	QUIC	204	Protected Payload (KP0)

Longer Delays. Possible?

An HTTP Request to Voyager!

(In simulation)

- 18 hours (64800s) one-way delay
- Direct link, Earth and Voyager nodes
- HTTP over configured QUIC
- Full QUIC flow: connection establishment (1,2), request and response (4,5), connection close(7,8). Additional features (3,6)

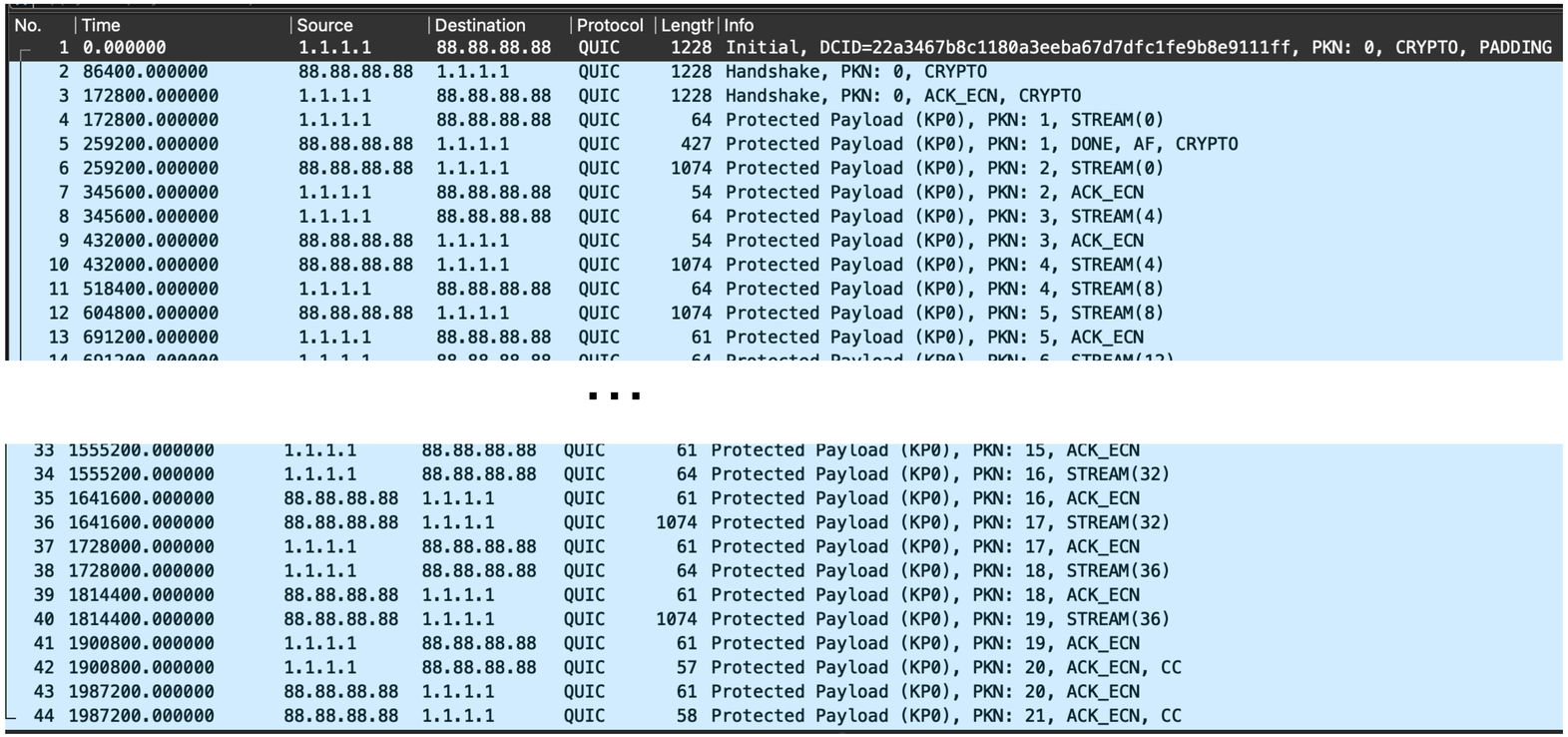
	Time	Source	Destination	Protocol	Length	Info
1	0.000000	192.168.65.33	192.168.65.25	QUIC	1242	Initial, DCID=d61b8e047f
2	64800.438656	192.168.65.25	192.168.65.33	QUIC	1380	Handshake, DCID=2f26ef8a
3	129600.8077…	192.168.65.33	192.168.65.25	QUIC	1242	Handshake, DCID=bf92a7a2
4	129600.8086…	192.168.65.33	192.168.65.25	QUIC	200	Protected Payload (KP0),
5	194401.1215…	192.168.65.25	192.168.65.33	QUIC	691	Protected Payload (KP0)
6	259201.4231…	192.168.65.33	192.168.65.25	QUIC	79	Protected Payload (KP0),
7	259201.4236…	192.168.65.33	192.168.65.25	QUIC	96	Protected Payload (KP0),
8	259201.4245…	192.168.65.33	192.168.65.25	QUIC	86	Protected Payload (KP0),

What about packet loss?

Let's try 5% packet loss over very long delay

Delay of 24 hours and 5% packet loss

- One way 24 hours delay(86400s), packet loss 5%, 10 times repeat HTTP request and response in the same connection
- Total time: 1987200s
  - same as without packet loss, since loss was recovered using the next packets
- Client data packets sent: 20, 3087 bytes
- Server data packets sent: 22, 12313 bytes
  - Server packets dropped: 2
  - (by the network simulation)
- Conclusion: QUIC recovered successfully and all data were properly sent reliably ✅



No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000	1.1.1.1	88.88.88.88	QUIC	1228	Initial, DCID=22a3467b8c1180a3eeba67d7dfc1fe9b8e9111ff, PKN: 0, CRYPTO, PADDING
2	86400.000000	88.88.88.88	1.1.1.1	QUIC	1228	Handshake, PKN: 0, CRYPTO
3	172800.000000	1.1.1.1	88.88.88.88	QUIC	1228	Handshake, PKN: 0, ACK_ECN, CRYPTO
4	172800.000000	1.1.1.1	88.88.88.88	QUIC	64	Protected Payload (KP0), PKN: 1, STREAM(0)
5	259200.000000	88.88.88.88	1.1.1.1	QUIC	427	Protected Payload (KP0), PKN: 1, DONE, AF, CRYPTO
6	259200.000000	88.88.88.88	1.1.1.1	QUIC	1074	Protected Payload (KP0), PKN: 2, STREAM(0)
7	345600.000000	1.1.1.1	88.88.88.88	QUIC	54	Protected Payload (KP0), PKN: 2, ACK_ECN
8	345600.000000	1.1.1.1	88.88.88.88	QUIC	64	Protected Payload (KP0), PKN: 3, STREAM(4)
9	432000.000000	88.88.88.88	1.1.1.1	QUIC	54	Protected Payload (KP0), PKN: 3, ACK_ECN
10	432000.000000	88.88.88.88	1.1.1.1	QUIC	1074	Protected Payload (KP0), PKN: 4, STREAM(4)
11	518400.000000	1.1.1.1	88.88.88.88	QUIC	64	Protected Payload (KP0), PKN: 4, STREAM(8)
12	604800.000000	88.88.88.88	1.1.1.1	QUIC	1074	Protected Payload (KP0), PKN: 5, STREAM(8)
13	691200.000000	1.1.1.1	88.88.88.88	QUIC	61	Protected Payload (KP0), PKN: 5, ACK_ECN
14	691200.000000	1.1.1.1	88.88.88.88	QUIC	64	Protected Payload (KP0), PKN: 6, STREAM(12)
...						
33	1555200.000000	1.1.1.1	88.88.88.88	QUIC	61	Protected Payload (KP0), PKN: 15, ACK_ECN
34	1555200.000000	1.1.1.1	88.88.88.88	QUIC	64	Protected Payload (KP0), PKN: 16, STREAM(32)
35	1641600.000000	88.88.88.88	1.1.1.1	QUIC	61	Protected Payload (KP0), PKN: 16, ACK_ECN
36	1641600.000000	88.88.88.88	1.1.1.1	QUIC	1074	Protected Payload (KP0), PKN: 17, STREAM(32)
37	1728000.000000	1.1.1.1	88.88.88.88	QUIC	61	Protected Payload (KP0), PKN: 17, ACK_ECN
38	1728000.000000	1.1.1.1	88.88.88.88	QUIC	64	Protected Payload (KP0), PKN: 18, STREAM(36)
39	1814400.000000	88.88.88.88	1.1.1.1	QUIC	61	Protected Payload (KP0), PKN: 18, ACK_ECN
40	1814400.000000	88.88.88.88	1.1.1.1	QUIC	1074	Protected Payload (KP0), PKN: 19, STREAM(36)
41	1900800.000000	1.1.1.1	88.88.88.88	QUIC	61	Protected Payload (KP0), PKN: 19, ACK_ECN
42	1900800.000000	1.1.1.1	88.88.88.88	QUIC	57	Protected Payload (KP0), PKN: 20, ACK_ECN, CC
43	1987200.000000	88.88.88.88	1.1.1.1	QUIC	61	Protected Payload (KP0), PKN: 20, ACK_ECN
44	1987200.000000	88.88.88.88	1.1.1.1	QUIC	58	Protected Payload (KP0), PKN: 21, ACK_ECN, CC

What about Network Management? QoS? Streaming?

Network Services

- Network Management: use SNMP/UDP (IETF deprecated) or NETCONF-RESTCONF/QUIC
- QoS: use the whole IP QoS/TE toolkit; apply based on source/destination addresses, diffserv marking, port/service, flow label, ...
- Naming: use DNS locally (on celestial body network)
- Emergency messaging: may use terrestrial framework (ECRIT)
- Time distribution: use NTP
- Media/Streaming: many choices: RTP, HTTP, MoQ, ...

Conclusion and More Information

- The Internet Protocol Suite is being deployed in deep space by:
  - Temporarily buffering IP packets in forwarders facing intermittence
  - Configuring QUIC transport with a space profile or use UDP
  - For applications, modifying timeouts appropriately and apply asynchronous design
- Advantages: much lower costs, lower risks, proven technology, faster to develop, secure,
- Who is deploying IP to Moon? Nokia, KDDI, China, LNIS(NASA, ESA, JAXA, Lunar service providers, ...)

- For more information:
  - Deep Space IP initiative: https://deepspaceip.github.io
  - QUIC simulation engine: https://github.com/aochagavia/quinn-workbench
  - IETF tiptop working group: https://datatracker.ietf.org/group/tiptop/about/
- Contact information:
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