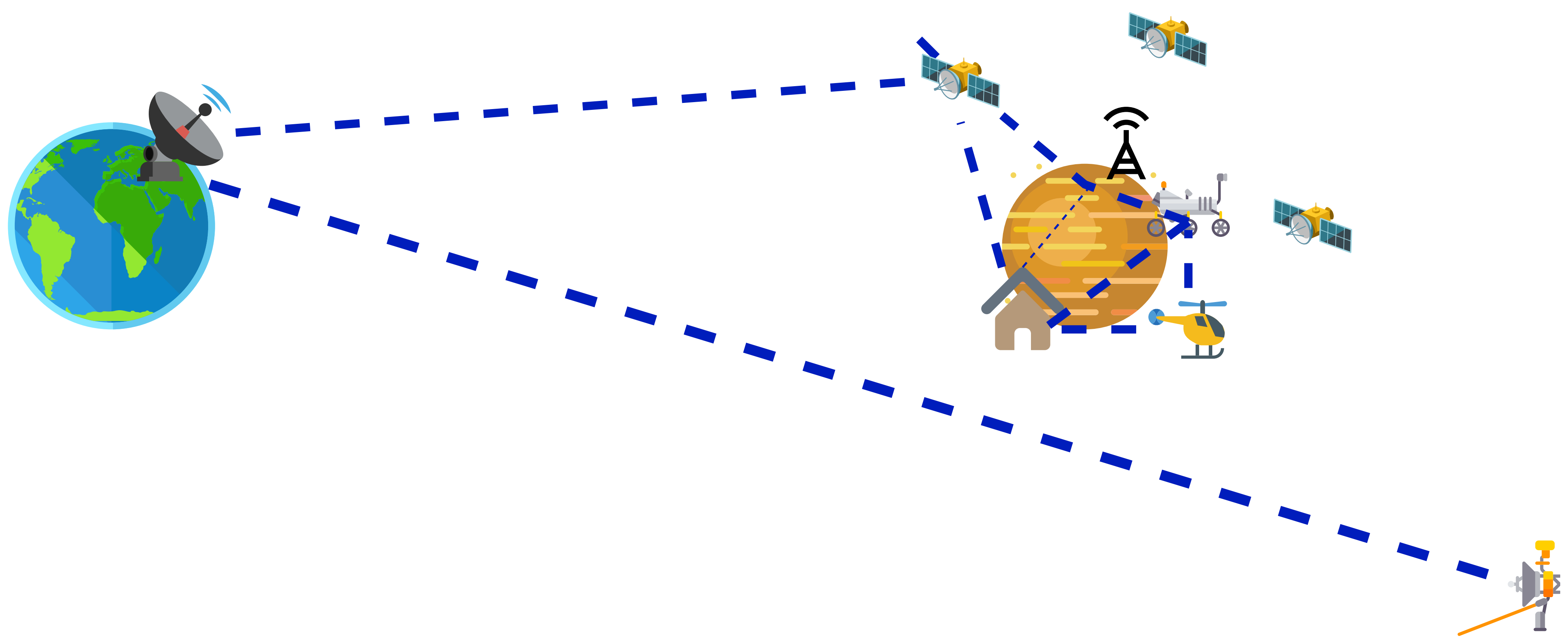

IP networking in Deep Space

Apricot 2026, Jakarta
2026-02

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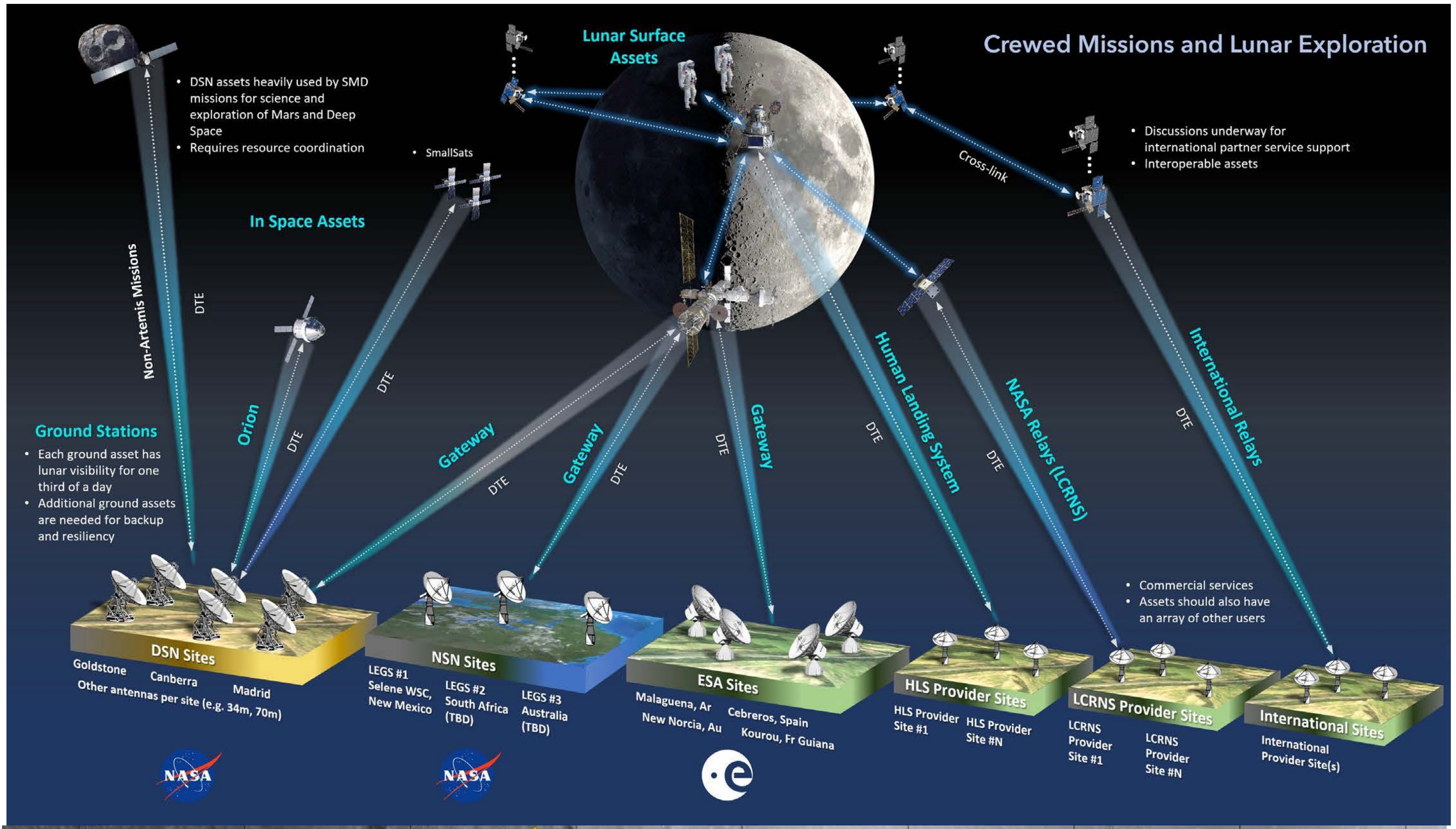
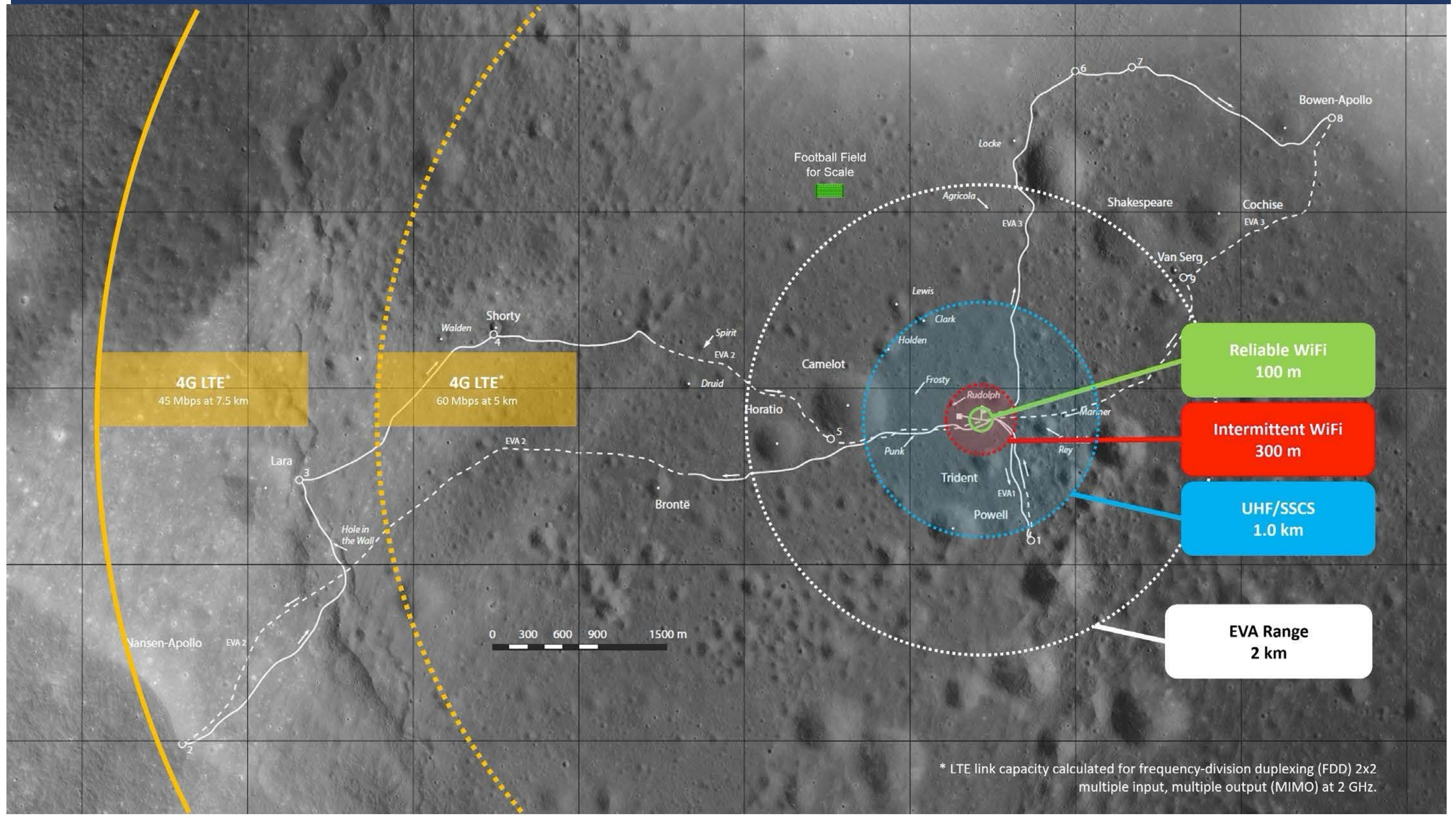
How Do/Will We Communicate in Deep Space?

Moon Comms Deployment

- Assets:
  - (Earth) Ground stations/Antennas
  - Communication relay orbiters
  - Celestial body surface assets: habitats, rovers, ...

- Link layers:
  - since 1960's: DTE using CCSDS
  - New:
    - surface (and orbital): 3GPP (5G/6G) and 802.X (WIFI)
    - Deep space (and orbital): CCSDS

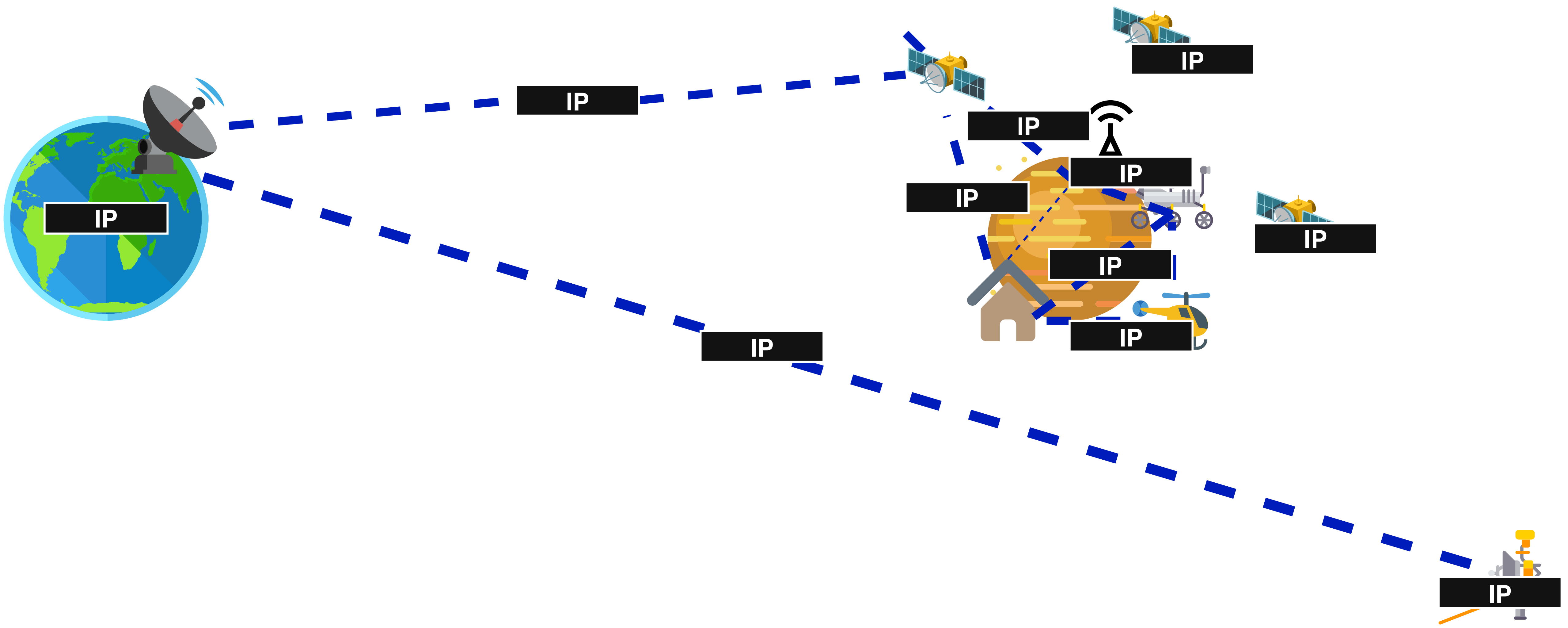




Moon Comms Deployment

With Networking Layer

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



- 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
  - Costs
  - Purpose
  - Challenges

* 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

What's the problem?

(network engineering)

Delay

- Earth-Moon: ~2 sec. one-way delay
- Earth-Mars: ~4-22 minutes one-way delay
- Earth-Voyager: ~24 hours one-way delay

- Not the typical (Earth) Internet delays, but ...
- Consequence: unconfigured stack (application, transport, ...) will timeout, retry, timeout, ...

What/How to Fix?

Configure Time-Related Variables

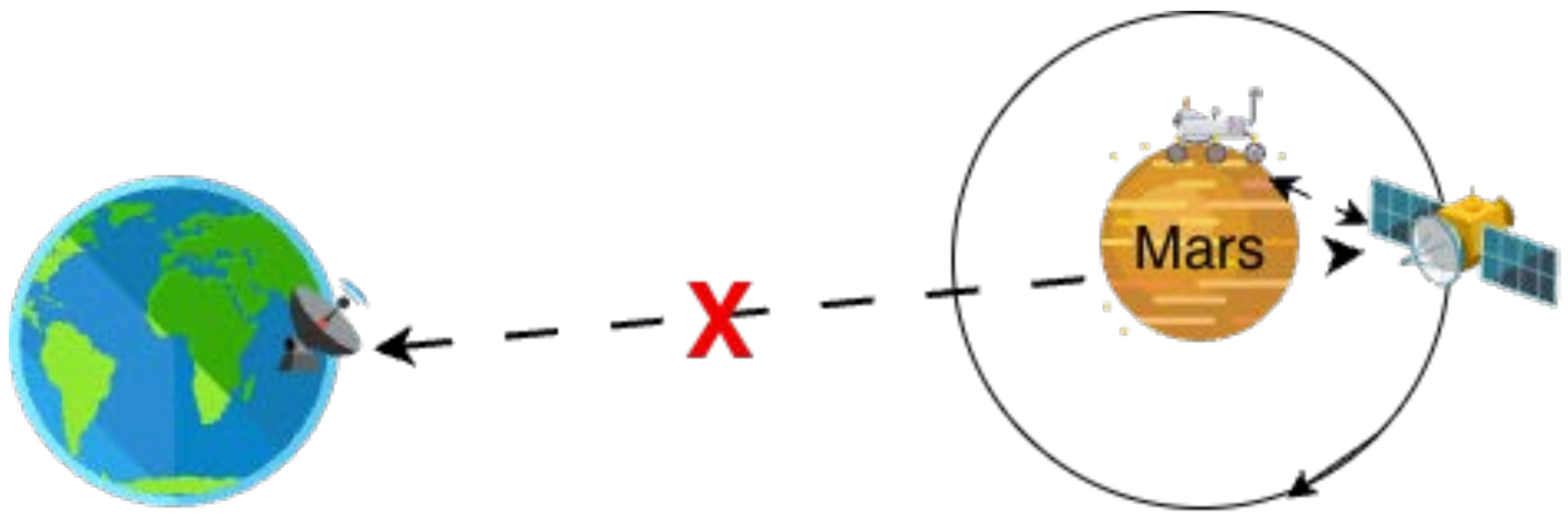
- "Easy"
  - Change the time-related variables, such as timeouts, response expectations, ... Example: curl -m <delay_value>
  - Based on (known in advance) expected delays
  - Where?
    - Applications, application protocols, transport. (IP and UDP have no notion of time)
- Caveat:
  - Forget immediate reactions, interactivity. Asynchronous is the paradigm. Fast reactivity to events not possible. Remote management is not interactive or fast.

Done?

Not Quite...

Intermittence/Disruptions

- Until "full" coverage around a celestial body is achieved by a constellation of connected satellites (with inter-satellite lasers)
  - There will be disruptions: a satellite becomes out of the view as it passes on the other side of the celestial body
- This intermittence creates:
  - Variability in delays:
    - Moon example: while orbiter is in view, delay = 2 seconds, then orbiter goes on the other side: 2 hours next pass.
    - Internet (transport) sees variability in round trip time. It knows how to deal with it.
      - But expectations on values and variability is different.
      - Cause is usually congestion, which has its own way to recover
      - In space, variability in delay is most often not congestion
  - Packet drops: a packet received by an orbiter/satellite that has no route to its destination will be dropped, as per IP forwarding behaviour



Okay. Just wait for full constellations!

Full Constellations

- Mars requires many orbiters, each costs some money, and each journey takes some time...
- Moon coverage shall be accomplished earlier
- Until then, and to cover other issues, we need a solution for delays and disruptions

Nothing else?

Yes…

Few Other Issues...

- Bandwidth is:
  - Limited
  - Asymmetric
- Links are:
  - Uni-directional
- Radiation, Solar storms
- Energy is very limited and maybe sporadic (waiting Sun to appear for your solar panels)
- ...

- Pretty similar to the IoT use case
- Reliability and recovery for any kind of event is key

What is the Solution?

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

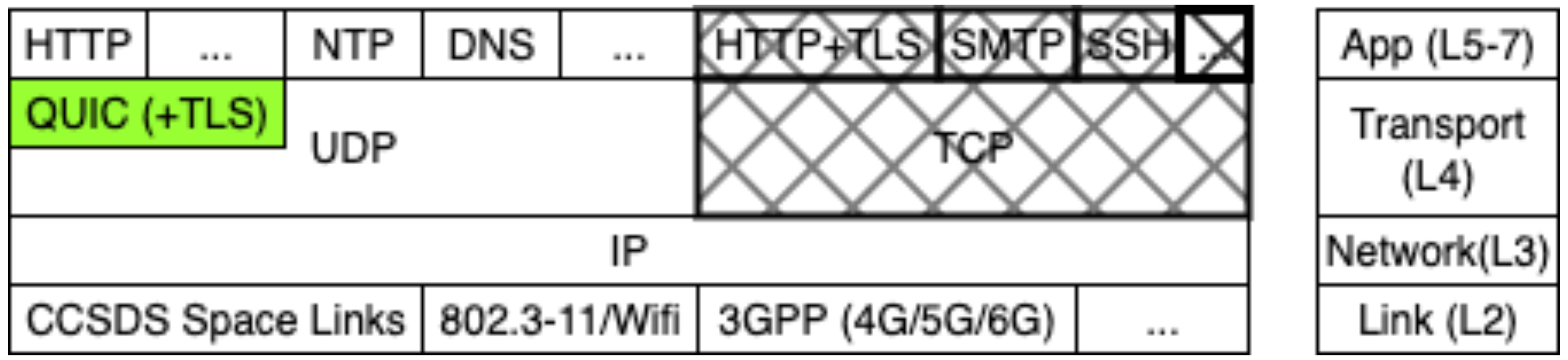
- IP and UDP (and HTTP) have no notion of time. Nothing to adapt.

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**

D. **Orchestration** of the whole network to optimize the use of links



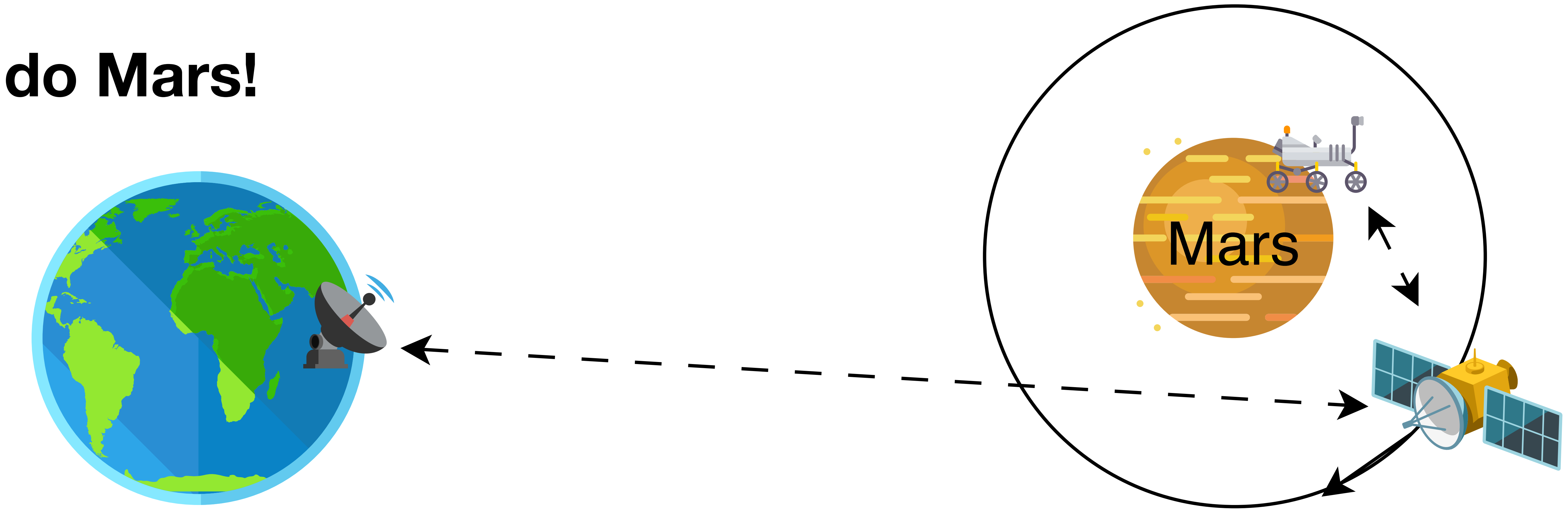
- TCP not suitable for space
- And everything above TCP
- Use profiled QUIC instead

Hey Marc, I'm not sure...

Does IP work in Deep Space?

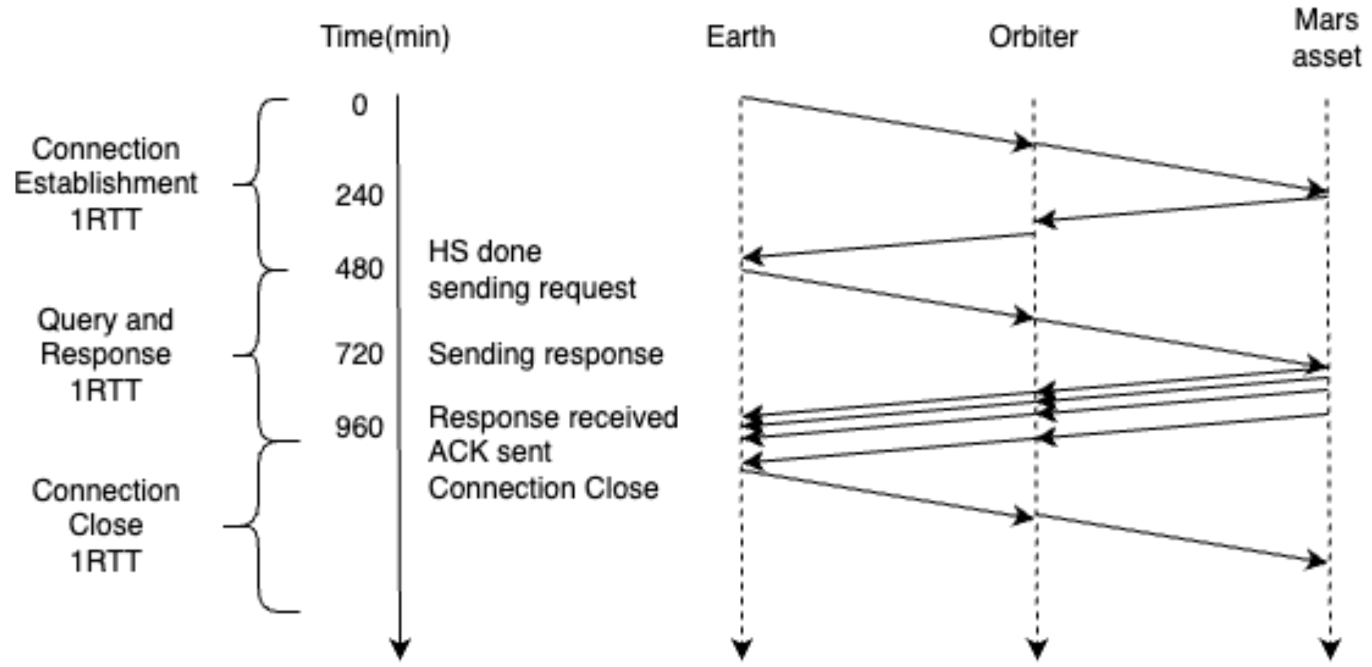
Let's put it to test!

Moon: ~2 seconds. Too easy ;-). Let's do Mars!

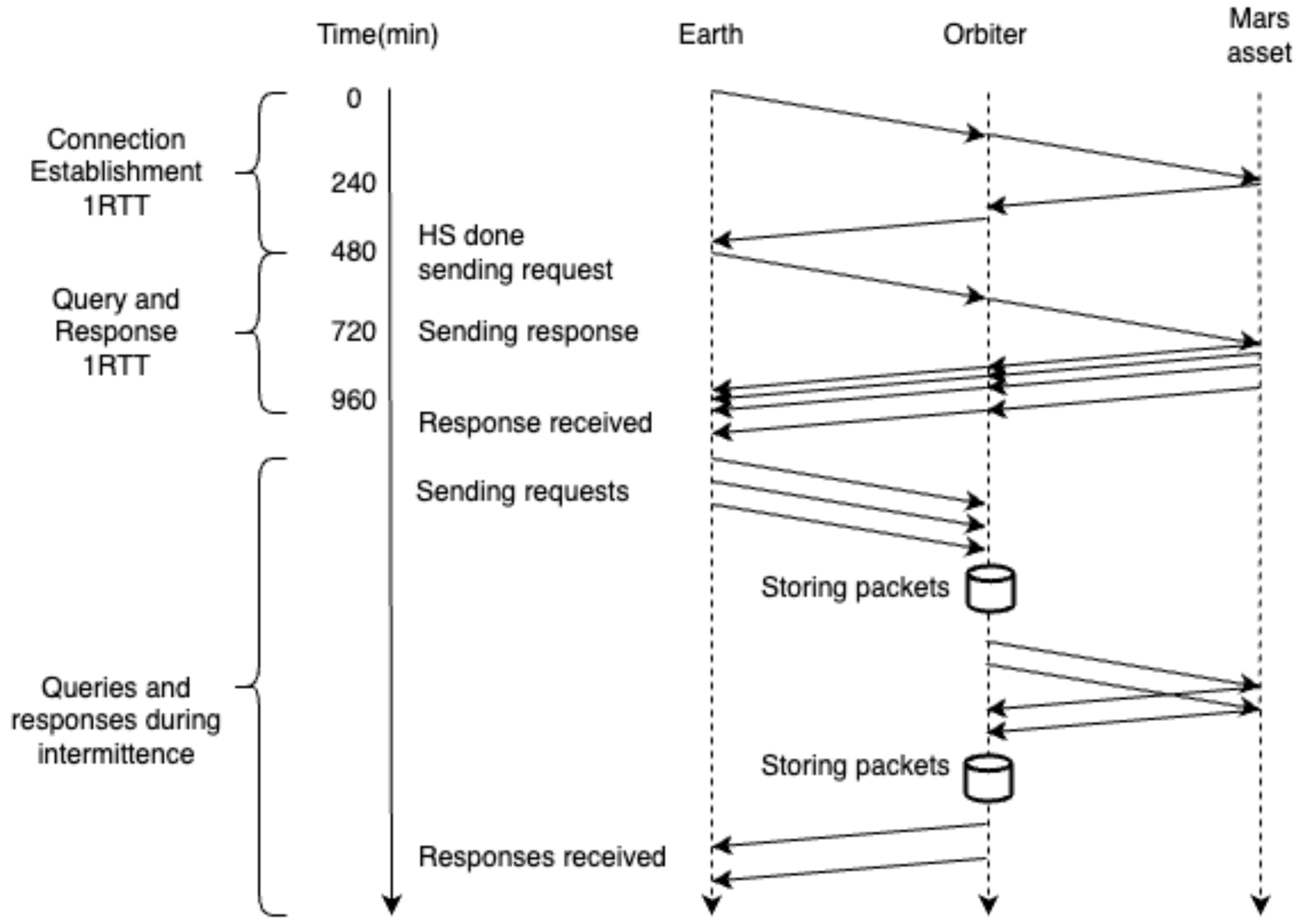


Simulation Results

1. Earth to Mars, 4 minutes (240s) one-way delay,
    - HTTP request/response over configured QUIC, two different QUIC implementations.
    - 1RTT for connection establishment, 1RTT for request/response; 16 minutes total



2. Intermittence: same as above but:
    - Requests sent every 15 minutes, no link every hour for 1 hour, our (Rust) implementation of IP packet storage/buffering
    - Packets were stored, RTT results in a sawtooth pattern. No packet loss.



Longer Delays?
Packet Loss?

Simulation Results (cont.)

3. Same as before, but Earth to Voyager!
    - 18 hours (64800s) one-way delay
    - 2 RTT (aka 72 hours) to receive response
4. 24 hour one-way delay, 5% (random) packet loss, 10 HTTP requests in sequence
    - 2 server packets were dropped (per netem random)
    - Lost packets were resent in the next RTT as additional frames into the current packets
    - All data was received properly in the same total time

What about Network Management? QoS? Streaming?

Network Services

- Network Management: use SNMP/UDP (IETF deprecated) or NETCONF-RESTCONF/QUIC. See: draft-ietf-netconf-over-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). See: draft-many-tiptop-dns
- Emergency messaging: may use terrestrial framework (ECRIT)
- Time distribution: use NTP
- Media/Streaming: many choices: RTP, HTTP, MoQ, ...

Difficult Problems

- Congestion:
  - Buffering packets means variable RTT, interpreted as congestion
- Routing at scale
  - Topology changes advertisements will arrive too late
- Key lifecycle
  - Long-lived connections may need different key renewals
  - Certificate validation cannot be done by going back to Earth

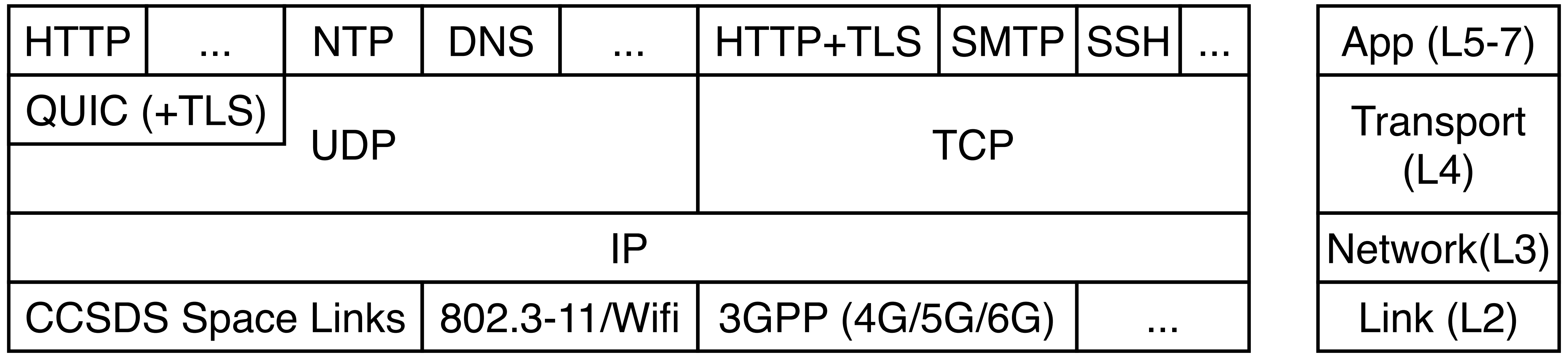
Conclusion and More Information

- 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 plain UDP
  - For applications, modifying timeouts appropriately and apply asynchronous design
- More work to do: IETF TIPTOP working group. Please join and contribute!

- For more information:
  - Deep Space IP initiative: https://deepspaceip.github.io
  - Deep Space IP Toolkit: QUIC simulation engine, IP buffering, Header compression, applications: https://github.com/deepspaceip
  - IETF tiptop working group: https://datatracker.ietf.org/group/tiptop/about/
  - Deep Space IP Discord Channel. (Contact me to get an invite)
- Contact information:
  - Marc Blanchet, Viagenie, marc.blanchet@viagenie.ca

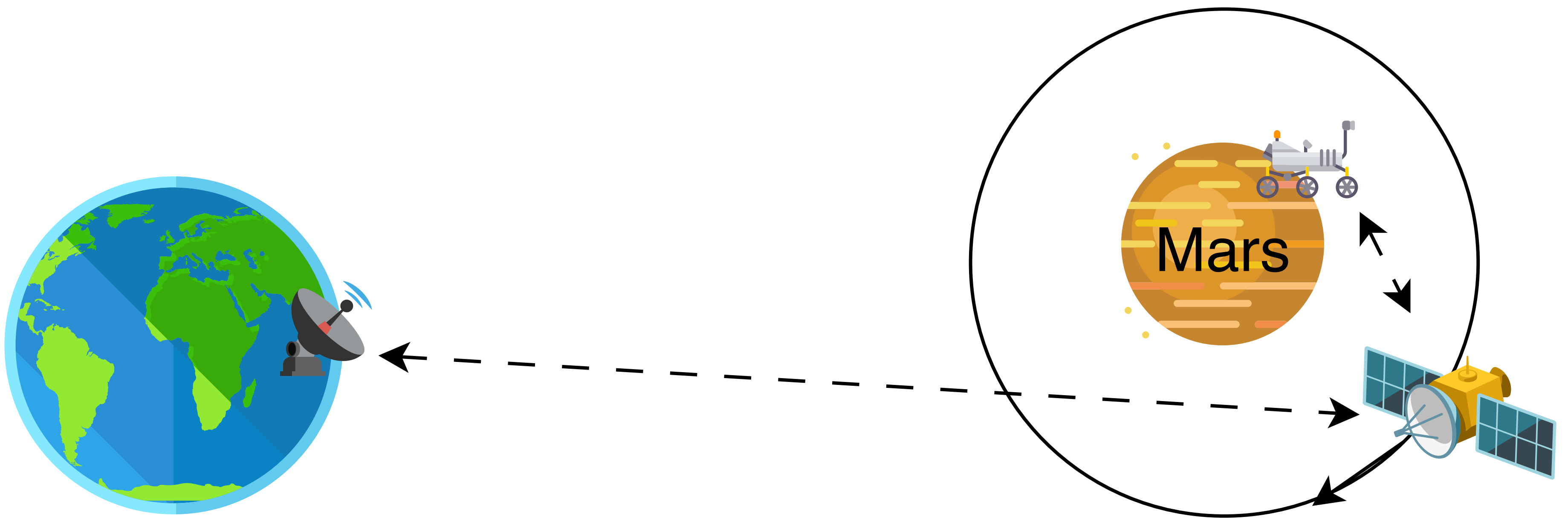
Reminder: IP Network Layer

- **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.
- Routing/forwarding is based on very simple identifiers in the base header: destination address. **Aggregation is possible because of hierarchical addressing**.
- **API (at all levels) is known**, stable and used for all applications

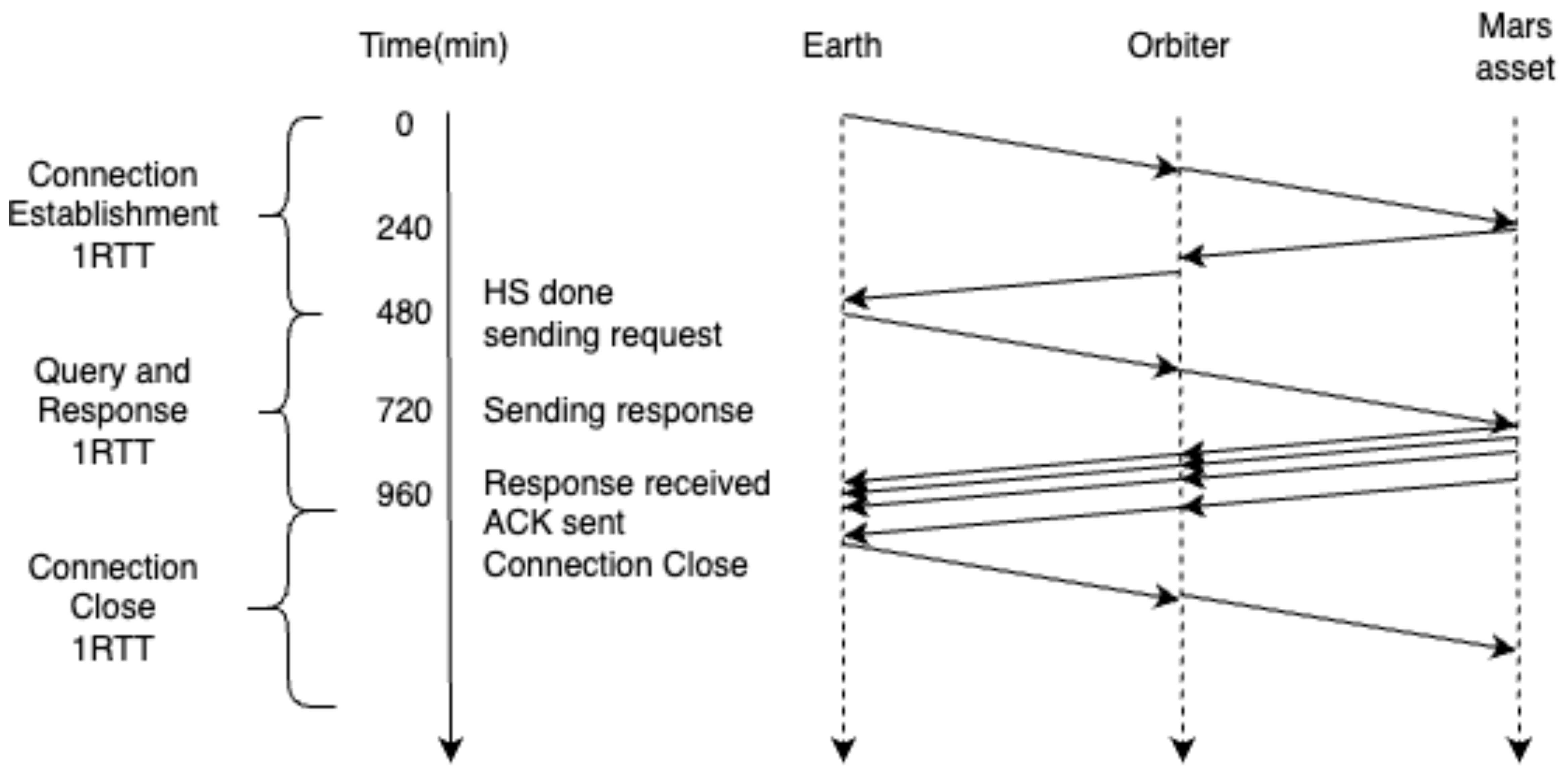


Appendix: Detailed Simulation Results

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 (Quinn, Quiche), configured for this expected delay**



Client Wireshark

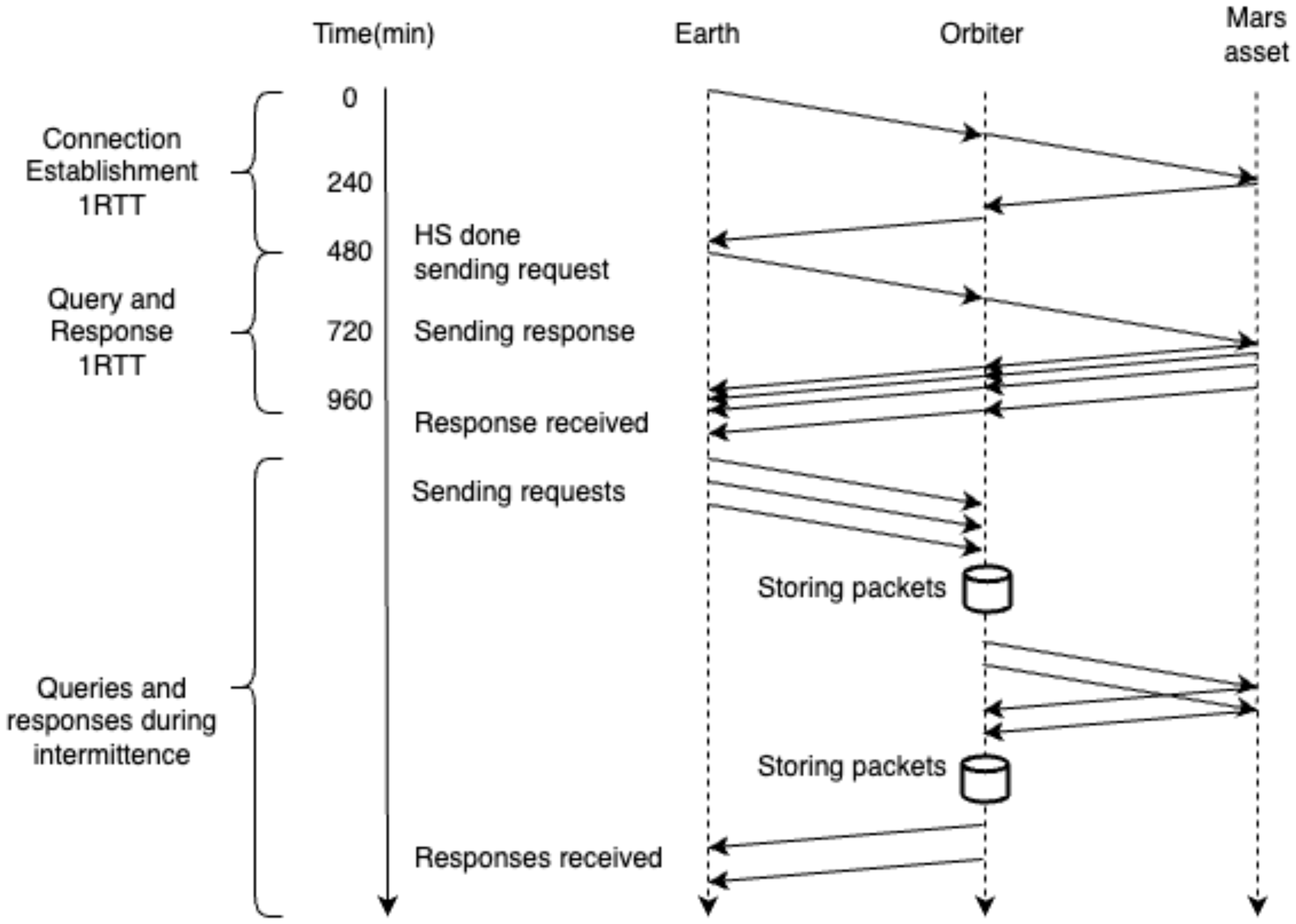
No.	Time	Source	Destination	Protoc	Length	Info
1	0.000000	192.168.40.1	192.168.42.1	QUIC	1242	Initial, DCID=ba7bb2be15d544e9aa76900070e41a9bacaa826e, SCID=dbd14607fed99229, PKN: 0, CRYPTO, PADDING
2	240.763219	192.168.42.1	192.168.40.1	QUIC	1686	Handshake, DCID=dbd14607fed99229, SCID=bc54d768409abe435a4c5c4904abe9788b088cc9, 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
- Our implementation of IP forwarding **and buffering**
    - 500 lines of Rust
    - Using linux tun interfaces



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 <u>24 hours</u> and 5% packet loss

- **One way 24 hours delay(86400s), packet loss 5%**, <u>10 times repeat</u> HTTP request and response in the same connection
- Total time: 1987200s
  - **<u>same as without packet loss</u>, 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
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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