Jet Propulsion Laboratory
California Institute of Technology

# Simultaneous Optical Links with the Inter-Satellite Omnidirectional Optical Communicator

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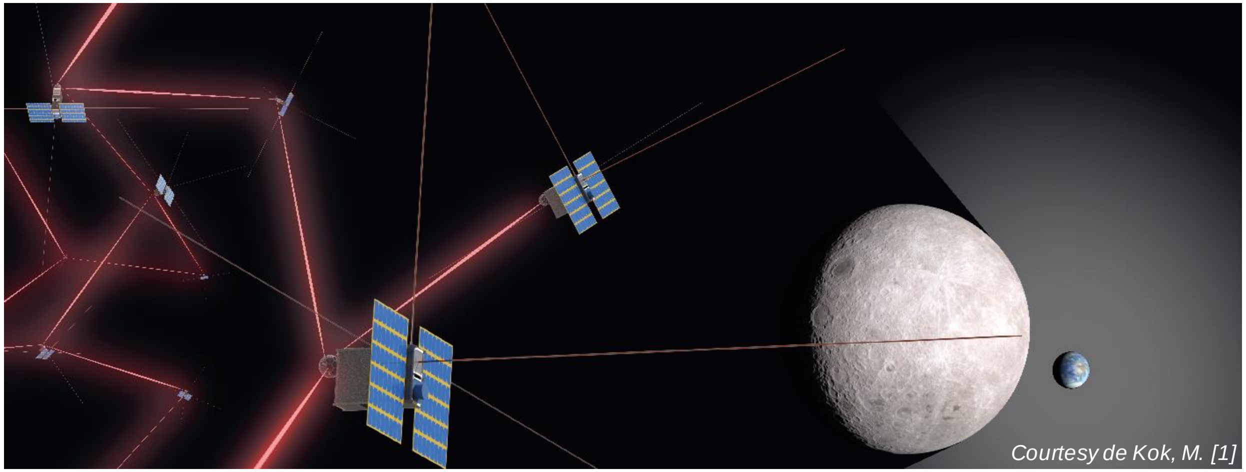
# Overview

- Motivation
- ISOC Terminal
- Link Budget
- Multiple Access Lasercom
- Conclusion

# Motivation

- Distributed systems of CubeSats can achieve unprecedented performance
  - E.g., CADRE [1]
- Higher levels of autonomy and on-orbit data volume need high data rates
  - 10 Mbps and GNSS-level navigation accuracy [2]


Courtesy de Kok, M. [1]

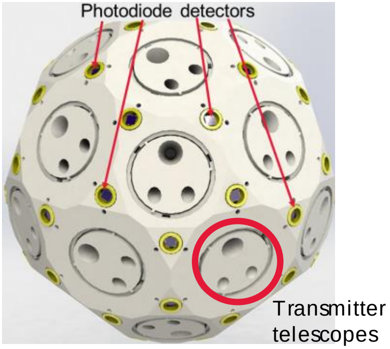
# Laser Communication

- Lasercom can meet capacity and navigation demands [3]
- Point-to-point links only

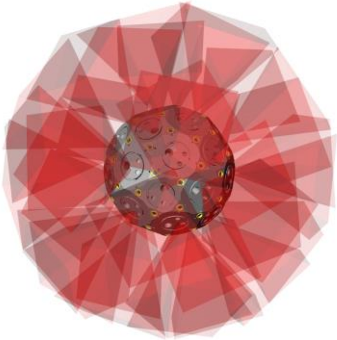
| | RF [4],[5] | Lasercom [6],[7] |
|---|---|---|
| Consumed Power | 12 W | 20 W |
| Data rate | 12.5 Mbps | 100 Mbps |
| Navigation accuracy | 40 cm | ~50 cm |
| Number of links | > 2 | 1 |

# Swarm Connectivity

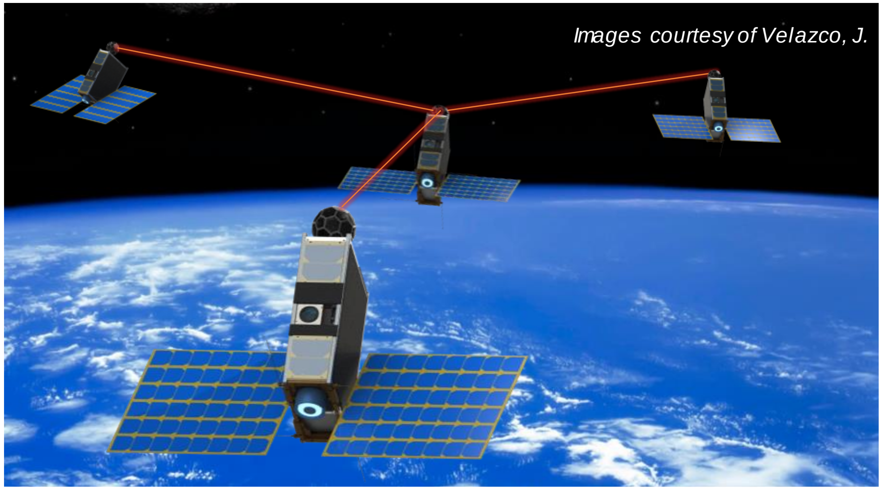
- JPL is investigating how to connect distributed systems with lasercom
- Intersatellite Optical Communicator (ISOC) [7]-[9]
  - Full-sky field of view
  - 1-Gbps crosslink rates at ~200 km separations
  - Multiple simultaneous links




ISOC Prototype



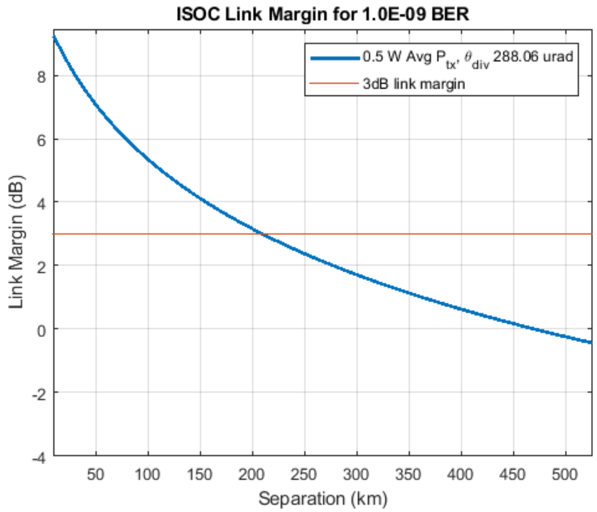
Full-sky FOV




Proposed ISOC mission Q4

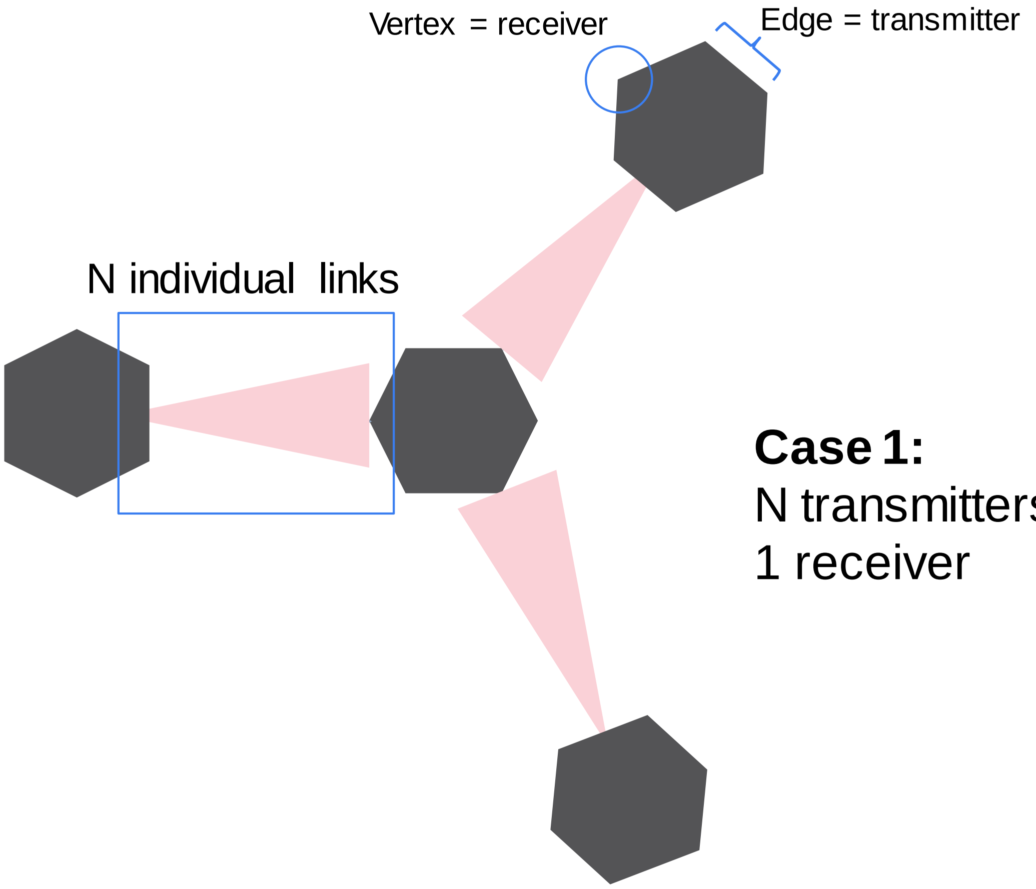
# ISOC Link Budget

- 1-Gbps links for BER 1E-09 at 226 km range achievable
  - 7.2-mm transmitter apertures
  - 6-mm diameter receiver lens



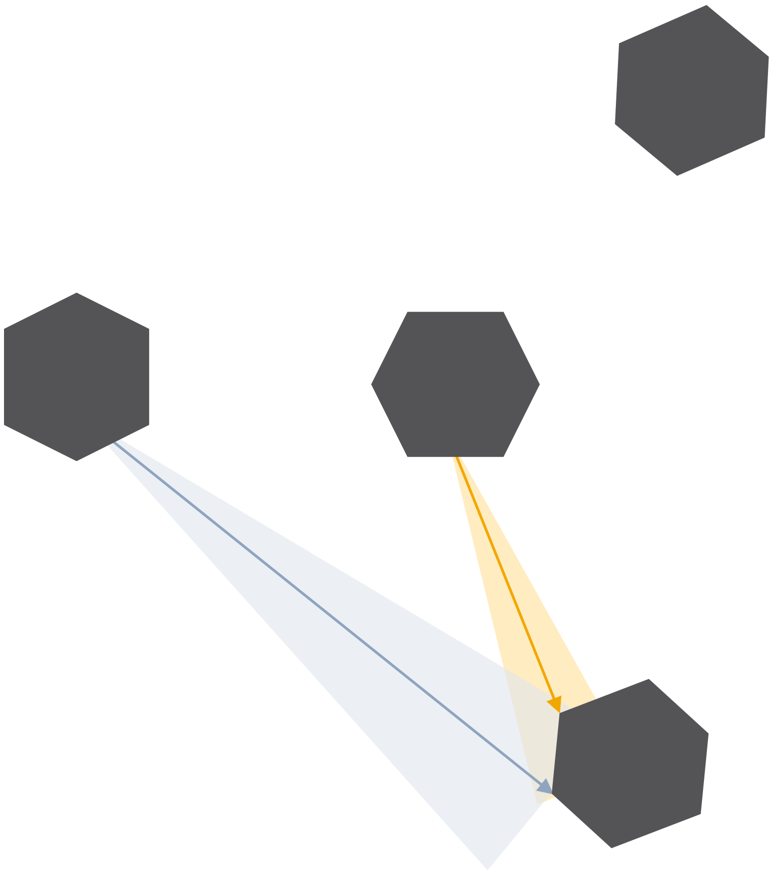

| System | | |
|---|---|---|
| Range | 226 | km |
| Wavelength | 850 | nm |
| Modulation | PPM-2 | - |
| Data Rate | 1 | Gbps |
| BER | 1.00E-09 | - |
| Free Space Path Loss | -250.48 | dB |
| Pointing Loss | -3 | dB |
| Background Noise | -120 | dBW |
| **Transmitter** | | |
| Output Power | 0 | dBW |
| Divergence | 138.27 | µrad |
| Gain | 89.23 | dBi |
| Coating Losses | -1 | dB |
| **APD Receiver** | | |
| Receiver Gain | 104.82 | dBi |
| Coating Losses | -1 | dB |
| Detector Gain | 100 | - |
| Responsivity | 0.5 | A/W |
| Dark Current | 0.1 | nA |
| Excess Noise Factor | 3.95 | - |
| Power Received | -71.01 | dBW |
| Power Required | -74.02 | dBW |
| Margin | 3.01 | - |

# Access Method




**Case 1:**
N transmitters,
1 receiver

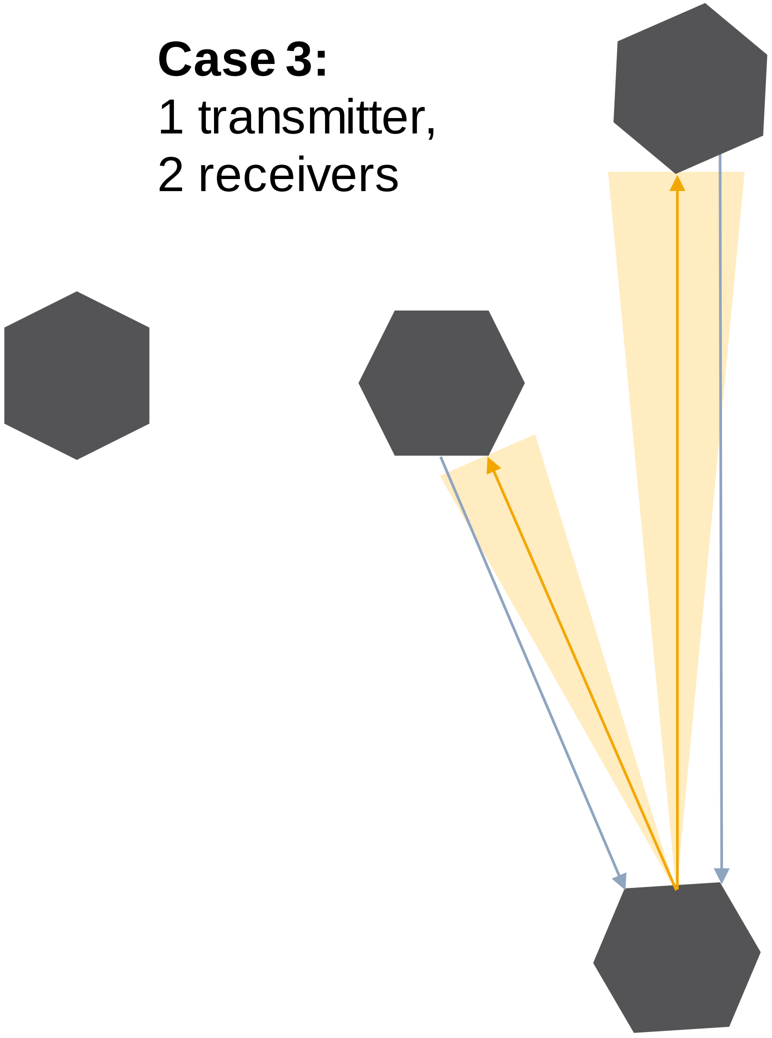
# Access Method



**Case 2:**
Interfering transmitters

# Access Method

**Case 3:**
1 transmitter,
2 receivers

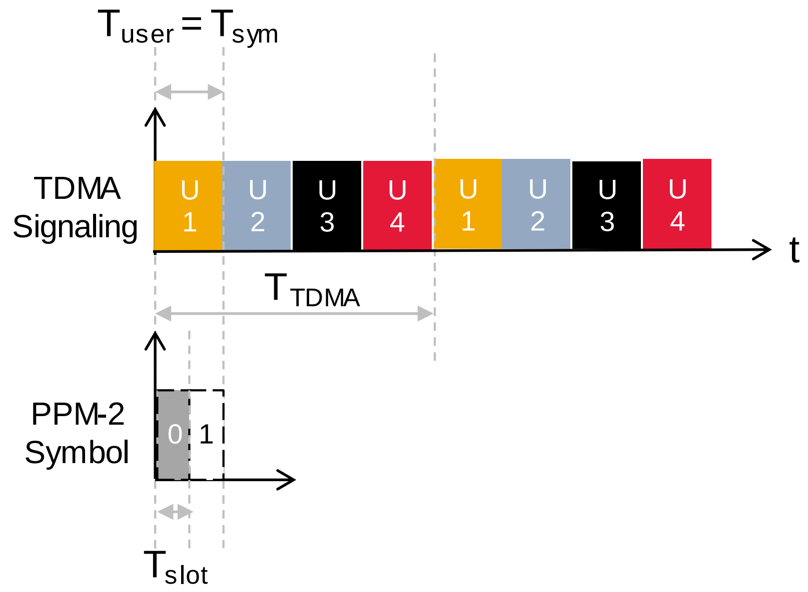


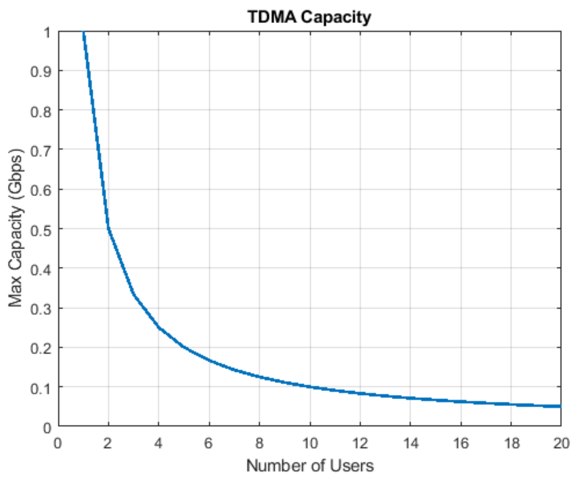
# Multiple Access

| Scheme | Wavelength Division | |
|---|---|---|
| | Discrete | Photonics |
| Capacity per user | | |
| Time utilization | | |
| Simplicity | | |
| Scalability | | |
| SWaP efficiency | | |
| TRL | | |
| AoA Compatible | | |

# TDMA Analysis

- Increasing number of “users” increases wait time
  - Decreases data rate
- Supports 4 links operating at 250 Mbps
- Hardware-limited to 12 links



# TDMA Analysis

**Benefits**

- Low complexity
- Easily deployable on COTS hardware (e.g., FPGA)
- Meets required swarm crosslink capacity (10 Mbps) even at reduced speeds

**Drawbacks**

- Doesn’t scale well with large number of users
- Only one link active at once (virtual simultaneous link)
- Users must wait for transmit slot

# Summary

- Distributed systems require advances in intersatellite links to enable network like behavior
- Lasercom supports required data rates and navigation in same system
- JPL is investigating the use of ISOC to connect swarms
  - Supports single high-rate links
- TDMA is a low-complexity multiple access method
  - Compatible with ISOC
  - Enables organized multiple simultaneous links for lasercom swarms

# References

[1] de Kok, M., Velazco, J. E., & Bentum, M. J. (2020) “CubeSat Array for Detection of RF Emissions from Exoplanets using Inter-Satellites Optical Communicators,” in IEEE Aerospace Conference Proceedings

[2] Horne, W., Kwadrat, C. F., & Edwards, B. L. (2002). Inter-Satellite Communications Considerations and Requirements for Distributed Spacecraft and Formation Flying Systems. https://doi.org/10.2514/6.2002-t5-53

[3] Davé, P. K., & Cahoy, K. (2019). Autonomous Satellite Navigation Using Intersatellite Laser Communications. American Astronautical Society (AAS) Astrodynamics Specialist Conference, 1–15.

[4] Pumpkin GNSS Receiver Module, Datasheet http://www.pumpkininc.com/space/datasheet/OEM719-Product-Sheet.pdf

[5] Altunc, S., Kegege, O., Bundick, S., Shaw, H., Schaire, S., Bussey, G., & O’Conor, D. (2015). X-band CubeSat Communication System Demonstration. *29th Annual AIAA/USU Conference on Small Satellites*, 1–9. Retrieved from http://digitalcommons.usu.edu/smallsat/2015/all2015/28

[6] Rose, T. S., Rowen, D. W., LaLumondiere, S., Werner, N. I., Linares, R., Faler, A., & Janson, S. W. (2018). Optical communications downlink from a 1.5U Cubesat: OCSD program. *International Conference on Space Optics — ICSO 2018*, *11180*. https://doi.org/10.1117/12.2535938

[7] CubeSat Laser Infrared CrosslinK Mission, NASA Website: https://www.nasa.gov/directorates/spacetech/small_spacecraft/cubesat_laser_infrared_crosslink

[8] Velazco, J. E., Griffin, J., Wernicke, D., DeNucci, A., Huleis, J., Velazco, J. E., & Zaman, I. U. (2018). Inter-satellite omnidirectional optical communicator for remote sensing. *SPIE Optical Engineering + Applications*, *10769*. https://doi.org/10.1117/12.2322367

[9] Velazco, J. E. (2019). Omnidirectional Optical Communicator. *IEEE Aerospace Conference Proceedings*, 1–6. https://doi.org/10.1109/AERO.2019.8741924

[10] Sanchez, J., & Velazco, J. E. (2020). Q4 – a CubeSat Mission to Demonstrate Omnidirectional Optical Communications. *IEEE Aerospace Conference Proceedings*.

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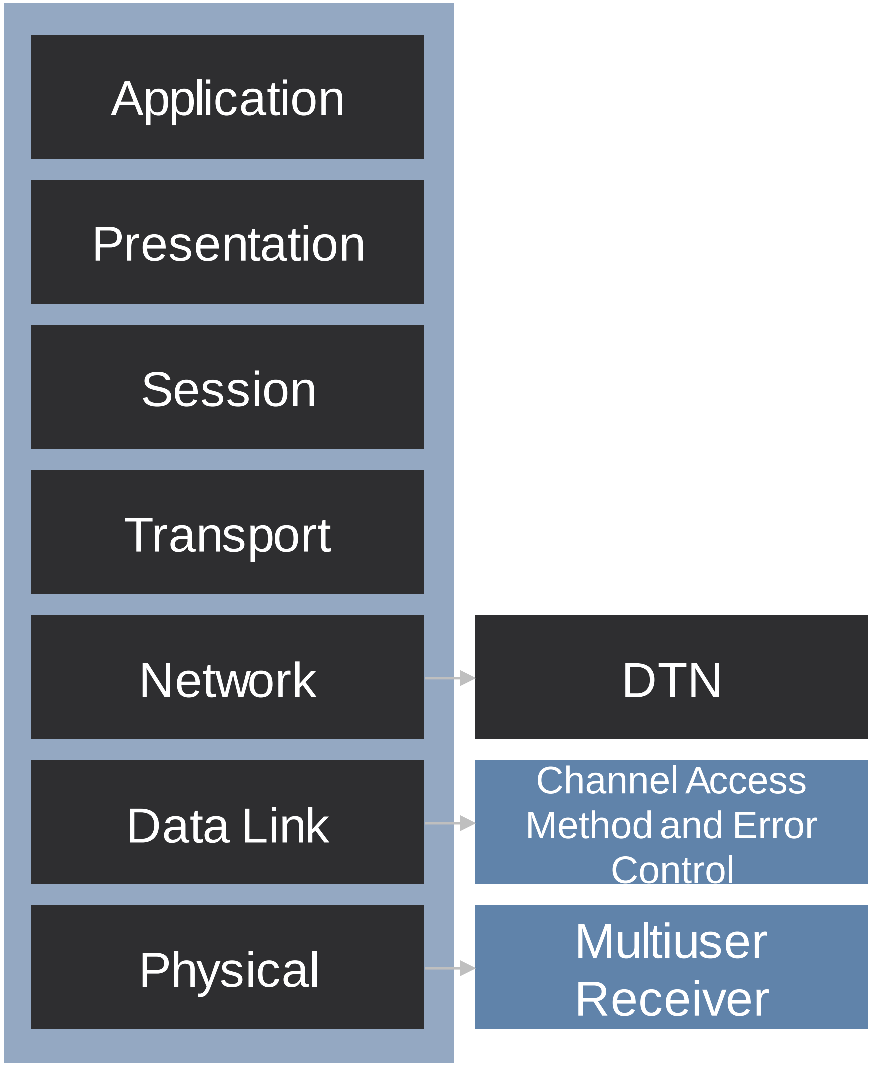
# Backup

# Framework

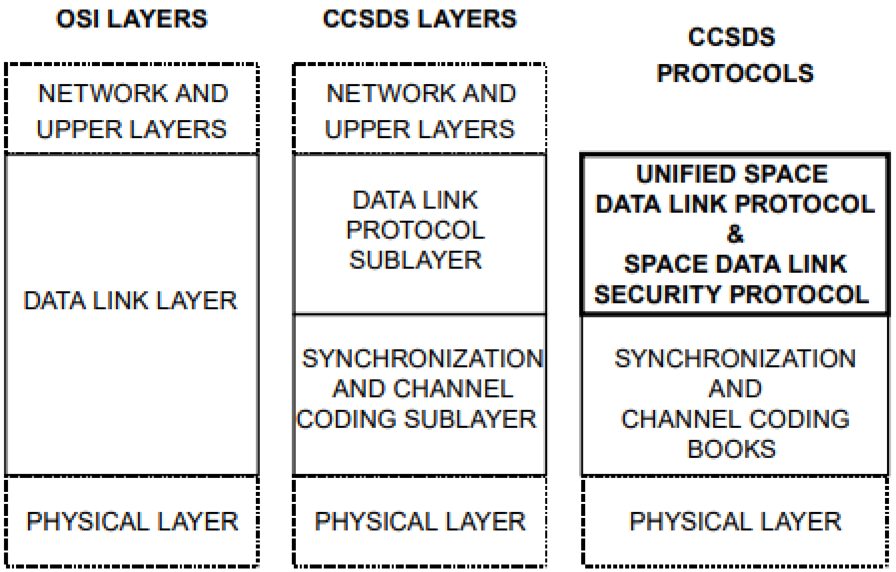
- OSI model partitions layers of a communication system
- Abstraction of problem that allows for future interoperability
- Compatible with DTN




OSI Model

# CCSDS

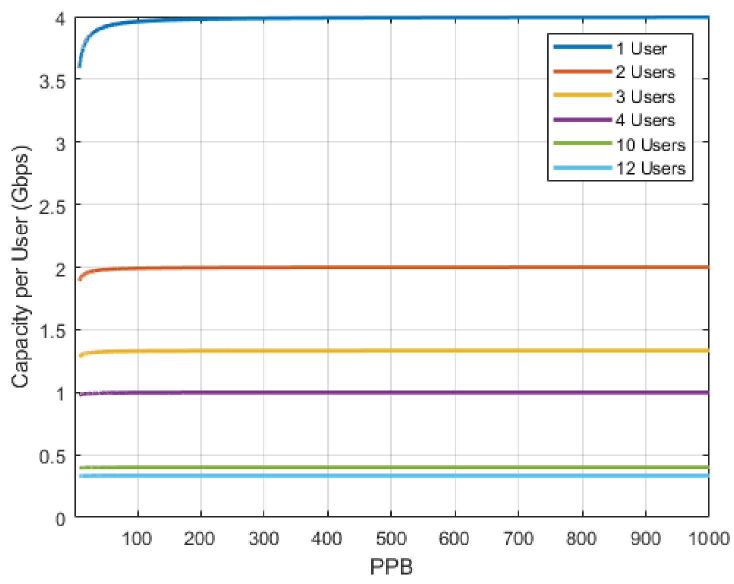
- No proposed standard for multiple simultaneous optical links
- New CCSDS blue book standards address point-to-point links

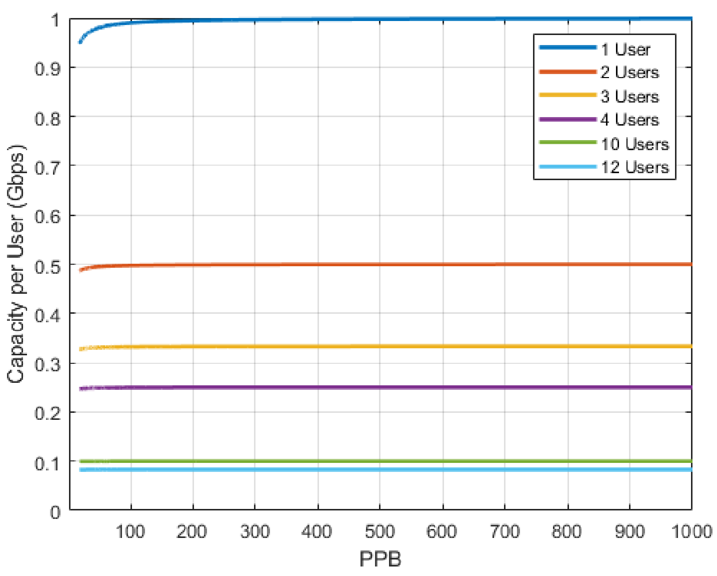


# TDMA Capacity

- $T_{slot}$ of 250 ps can achieve 4 links at 1 Gbps speeds
- Limited by VCSEL transmitter

- $T_{slot}$ of 1 ns (proposed)
- Low PPB impacts highest capacity links most



# FPGA Limitations

- Current ISOC backend uses a Virtex-7 FPGA
- All lines are multiplexed onto single line to reduce computational overhead
- This architecture limits total number of links to 12 assuming each line operates at 1 Gbps

| | Type | Max Performance[1] | Max Transceivers | Peak Bandwidth[2] |
|---|---|---|---|---|
| Virtex UltraScale+ | GTY/GTM | 32.75/58.0 | 128/48[3] | 8,384 Gb/s |
| Kintex UltraScale+ | GTH/GTY | 16.3/32.75 | 44/32 | 3,268 Gb/s |
| Virtex UltraScale | GTH/GTY | 16.3/30.5 | 60/60 | 5,616 Gb/s |
| Kintex UltraScale | GTH | 16.3 | 64 | 2,086 Gb/s |
| Virtex-7 | GTX/GTH/GTZ | 12.5/13.1/28.05 | 56/96/16[3] | 2,784 Gb/s |
| Kintex-7 | GTX | 12.5 | 32 | 800 Gb/s |
| Artix-7 | GTP | 6.6 | 16 | 211 Gb/s |
| Zynq UltraScale+ | GTR/GTH/GTY | 6.0/16.3/32.75 | 4/44/28 | 3,268 Gb/s |
| Zynq-7000 | GTX | 12.5 | 16 | 400 Gb/s |
| Spartan-6 | GTP | 3.2 | 8 | 51 Gb/s |