Exploring Integration: TSN with MRR-Based Passive Optical Wireless Architecture for Space- and Air-borne Communications

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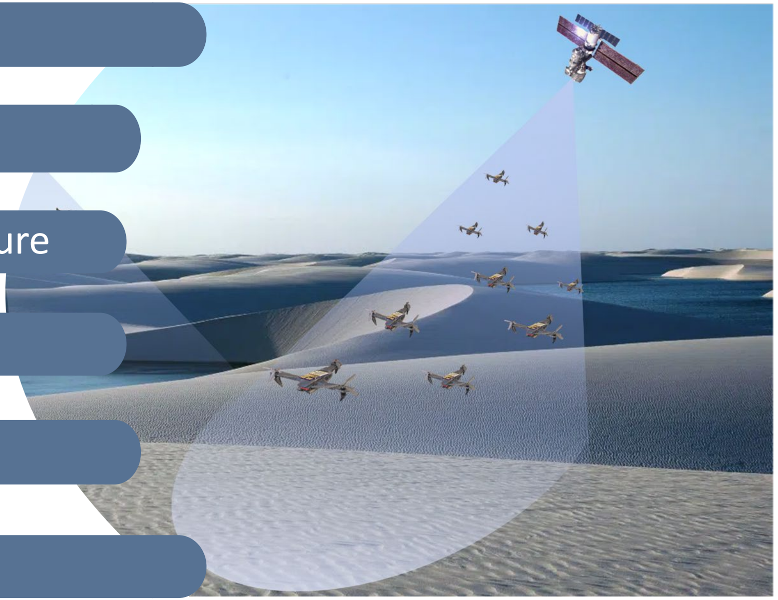
Outline

- Satellite onboard network and requirements
- Available solutions for satellite onboard networks
- TSN with MRR-based passive optical wireless architecture
- IEEE 802.1AS over MRR-based passive optical wireless
- Synchronization error evaluation
- Conclusion and future developments



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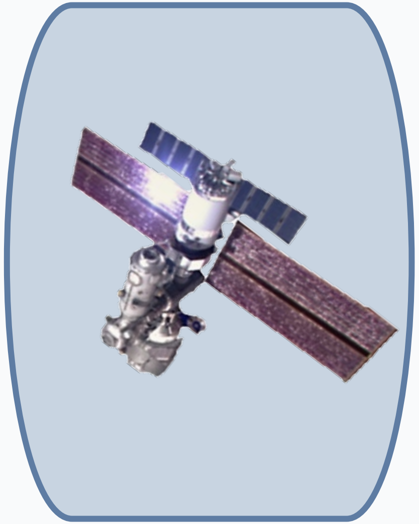
Satellite onboard network and requirements

Intra-communication system exchanges:

Guidance Navigation and **Control** data

Telemetry data



- Exchanges of **guidance, navigation, and control messages** within the spacecraft **require rigorous temporal synchronization** to ensure critical operations occur at the right moments
- Integrating **real-time onboard network** is **crucial** for mission success
- **Temporal precision** is crucial. Even small temporal deviations could compromise the success of critical operations or negatively impact the spacecraft's performance

Available solutions for satellite networks

Obsolete used solution

MIL-STD-1553B

- ✓ Reliability
- 1 *Mbps* bandwidth
- Topology inflexibility
- Poor reconfigurability

→

ETHERNET-BASED SOLUTIONS

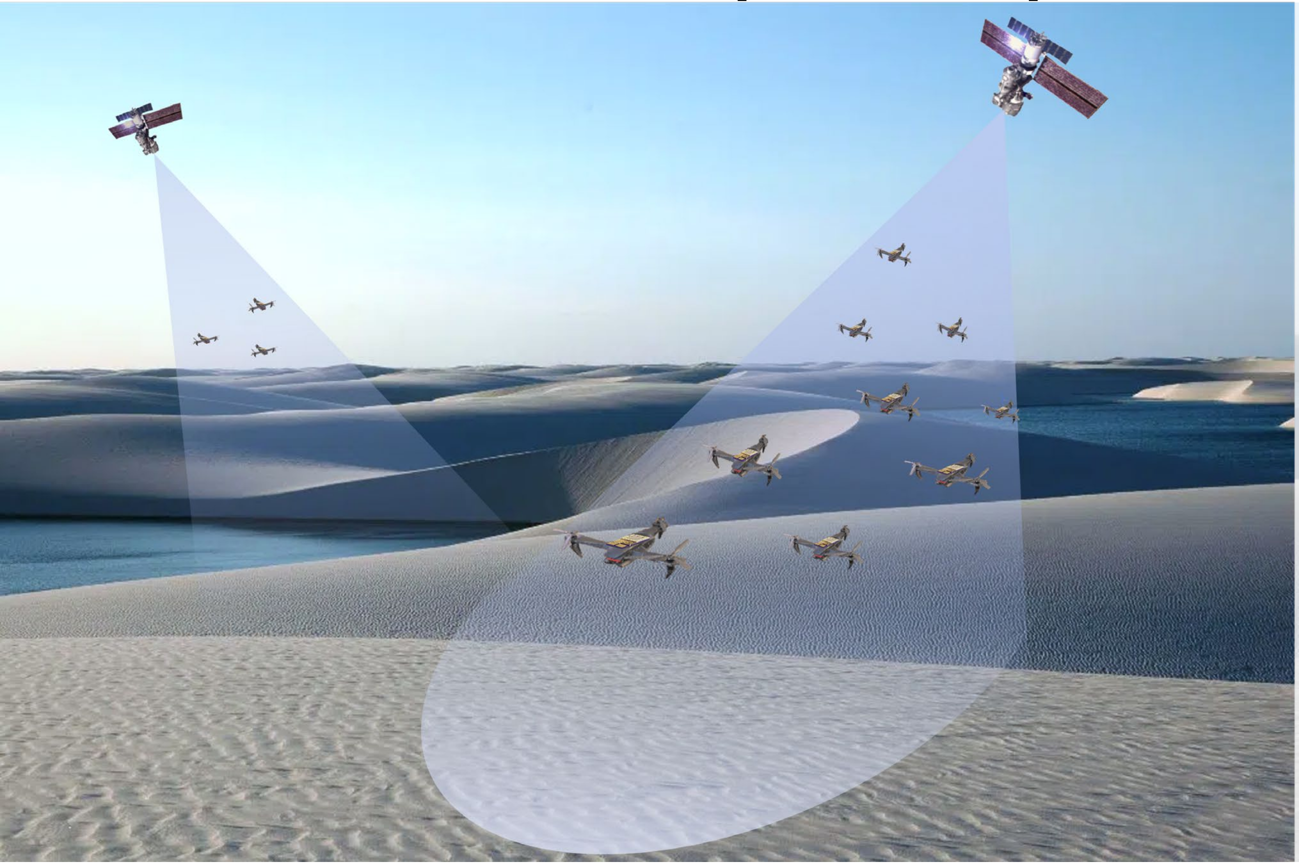
TTEthernet

- ✓ Up to 1 *Gbps* bandwidth
- ✓ Available
- High cost
- Proprietary

TSN

- ✓ Up to 1 *Gbps* bandwidth
- ✓ High Flexibility
- Complexity

TSN with MRR-based passive optical wireless overview



- Future terrestrial **exploration** will greatly benefit from a **wide-reaching communication network** in key regions
- Integrating Time Sensitive Networking **onboard spacecraft is crucial** for real-time applications like **positioning**, **navigation**, and **timing, coordinated autonomous vehicles**, safety operations, and **distributed sensing**

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TSN with MRR-based passive optical wireless overview

MRR-based passive optical wireless

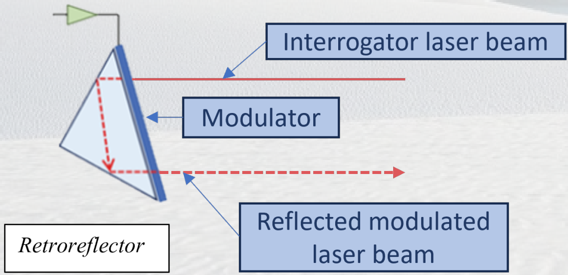
- Weight reduction
- Low power
- High bandwidth

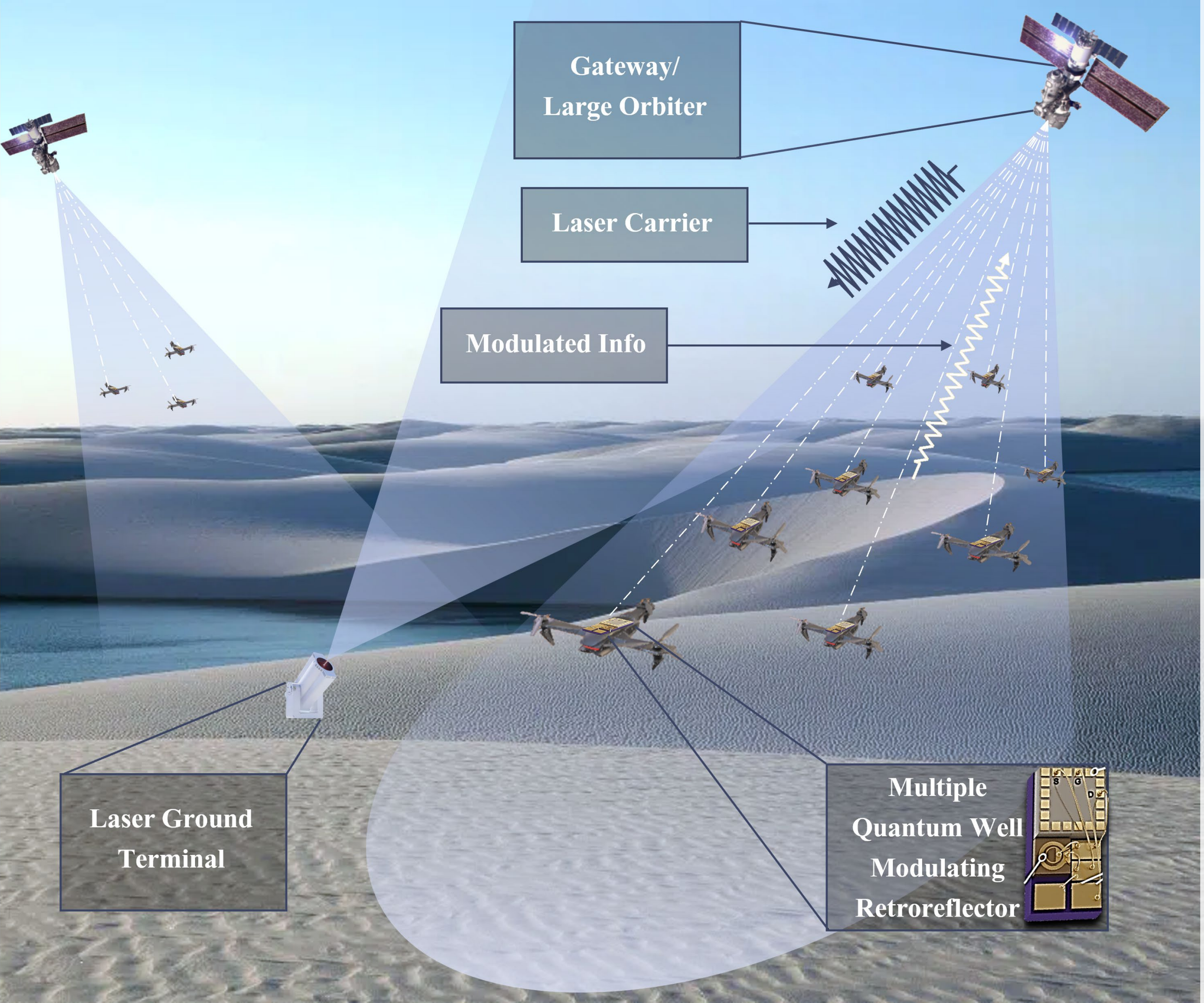
Onboard TSN network

- Interoperability
- Becoming widely used
- Low costs

Integration of TSN with MRR-based passive optical wireless for synchronizing UAVs

- **Orbiter** with **high-performance interrogator laser**
- **Unmanned Aerial Vehicle (UAV)** swarm executing **synchronized tasks** equipped with multiple **quantum well Modulating Retroreflectors (MRR)**



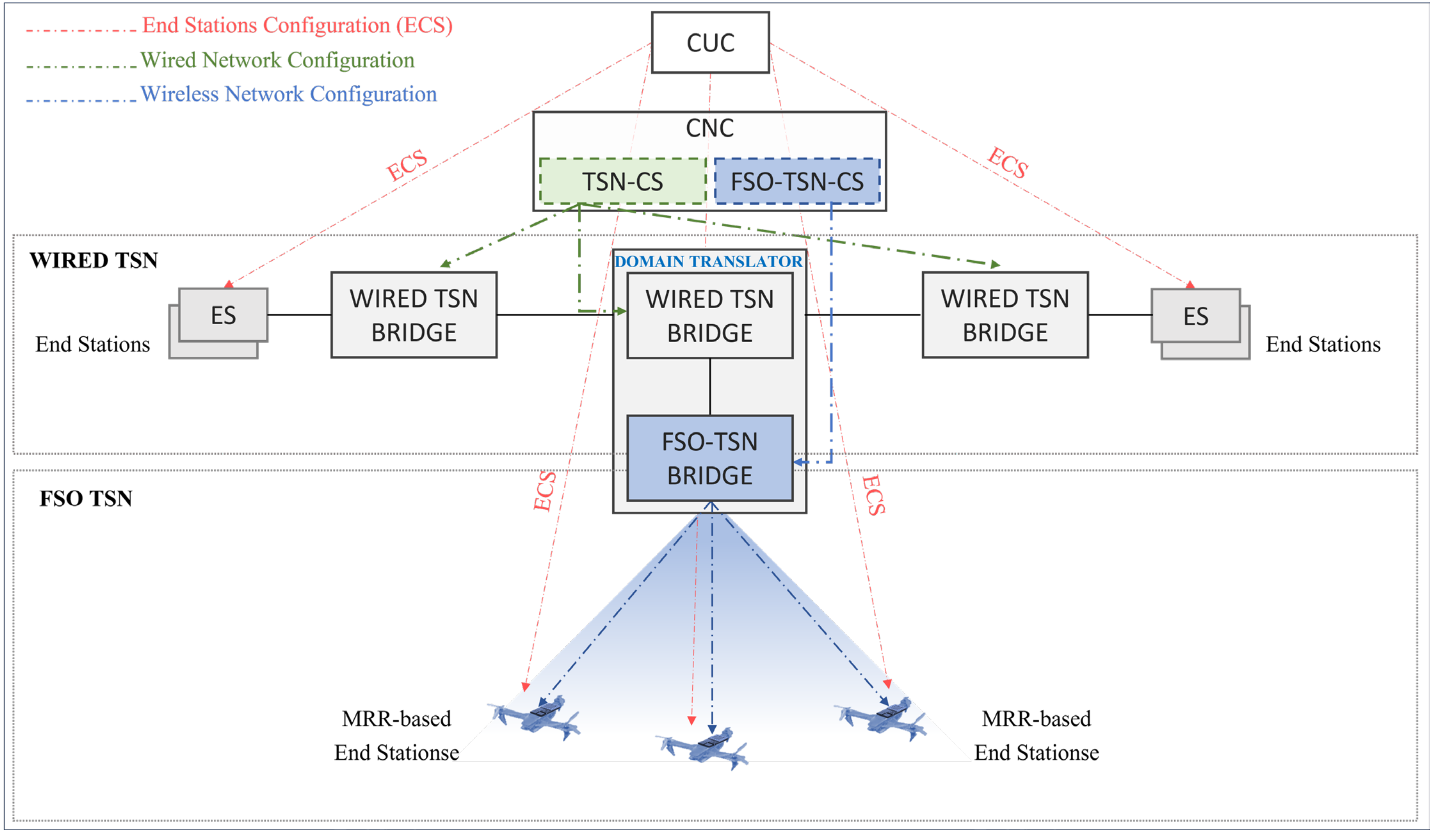


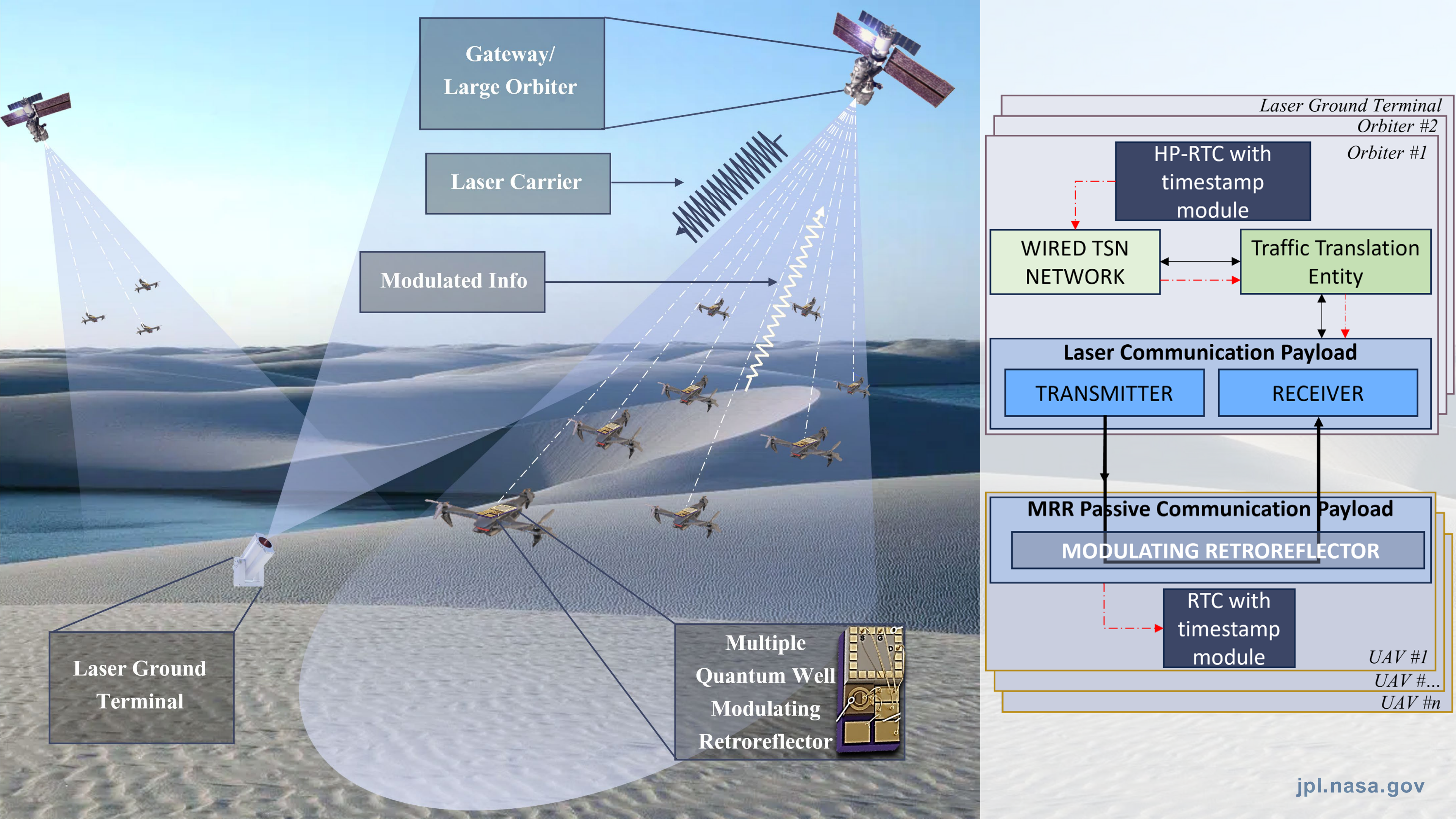
- **Hybrid orbiter TSN architecture** that includes **wired** and **wireless** interfaces, **enabling TSN tools** for **both wired and Free Space Optical** (FSO) **communication channels** with **MRR-based technology**
- **Laser ground terminal with high-performance free space laser communication payload**
- **UAVs** swarm executing **synchronized tasks** equipped with multiple **quantum well Modulating Retroreflectors (MRR)**

Onboard hybrid orbiter architecture

The network is centrally managed and configured with the **Central User Configuration** (CUC) and **Central Network Configuration** (CNC)

The **CNC** function **is split** in **wired and free space optical TSN configuration subsystem** (TSN-CS and FSO-TSN-CS)




Gateway/
Large Orbiter
Laser Carrier
Modulated Info
Laser Ground
Terminal
Multiple
Quantum Well
Modulating
Retroreflector
Laser Ground Terminal
Orbiter #2
Orbiter #1
HP-RTC with
timestamp
module
WIRED TSN
NETWORK
Traffic Translation
Entity
Laser Communication Payload
TRANSMITTER
RECEIVER
MRR Passive Communication Payload
MODULATING RETROREFLECTOR
RTC with
timestamp
module
UAV #1
UAV #...
UAV #n
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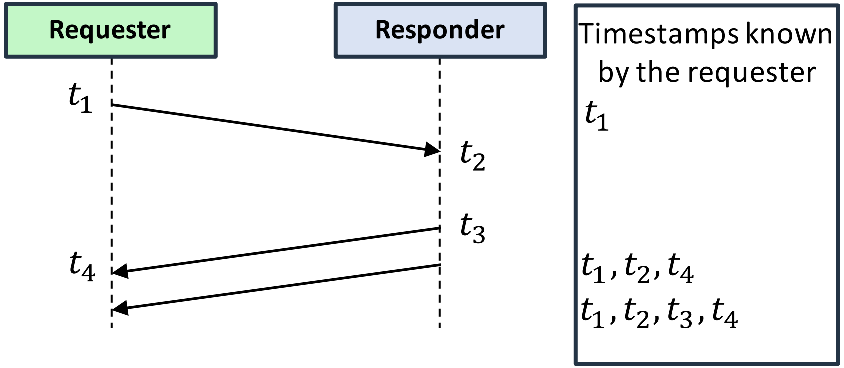
Time Synchronization over MRR-based passive optical communication

IEEE802.1AS

- Propagation delay measurement mechanism

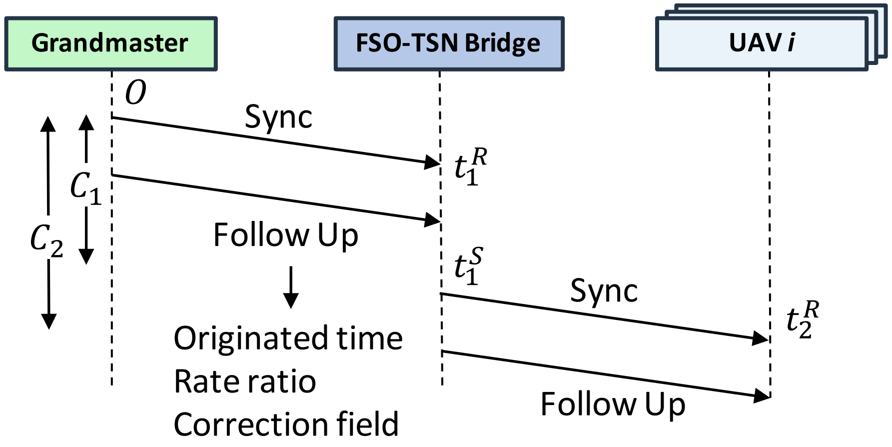


$$Delay \qquad D = \frac{(t_2 - t_3) + nr(t_4 - t1)}{2}$$

$$Neighbour\ rate\ ratio \qquad nr = \frac{f_{requester}}{f_{responder}}$$

$$Interval\ Delay \qquad I_p$$

- Synchronization information distribution mechanism



$$Rate\ ratio \qquad r_i = r_{i-1} * \ nr_i$$

$$Correction\ field \qquad C_i = C_{i-1} + D_i * r_{i-1} + (t_i^s - t_i^R) * r_{i-1} * nr_i$$

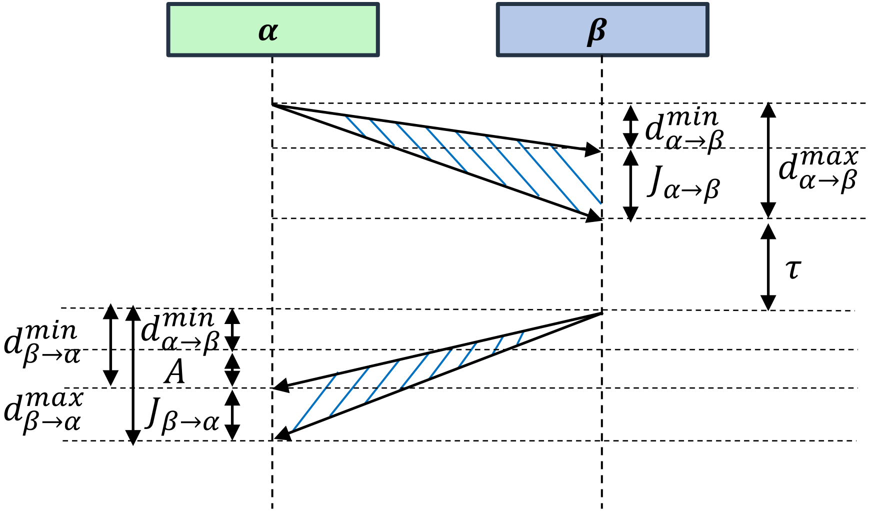
$$Clock\ Estimation \qquad GM_i(t) = O + C_{i-1} + D_i + (t_i^s - t_i^R)$$

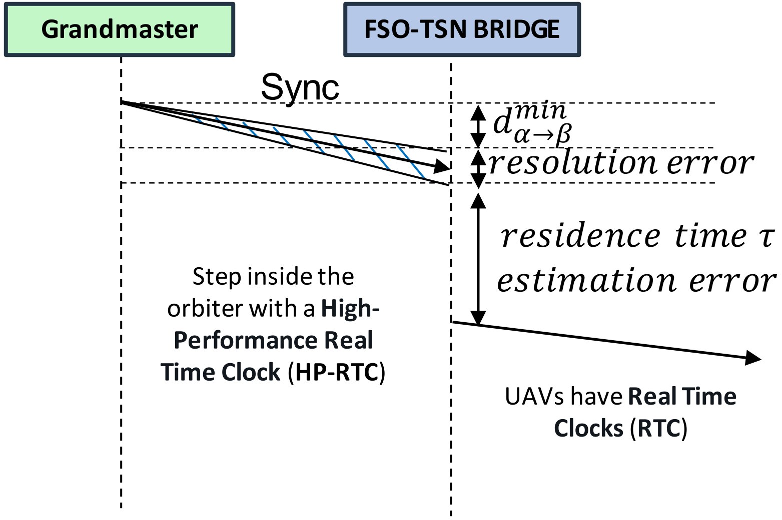
$$Interval\ Sync \qquad I_s$$

Synchronization error evaluation

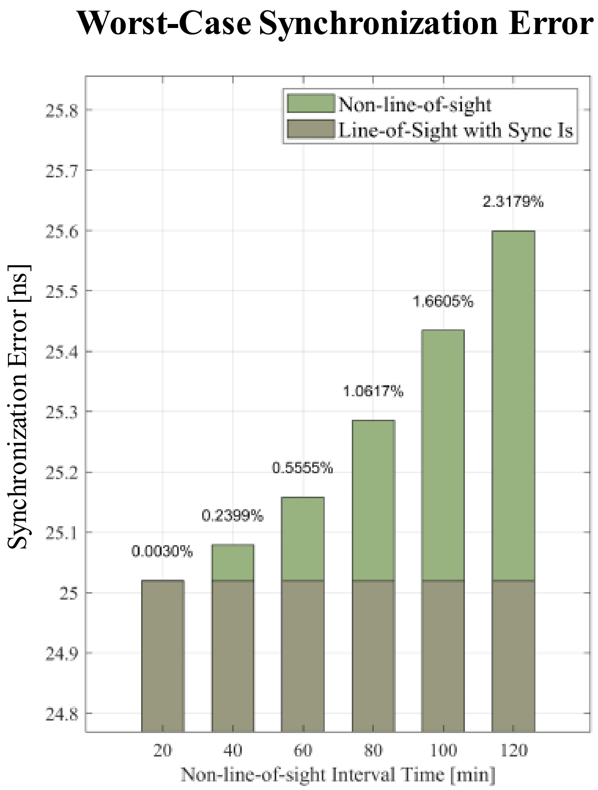
The delay $\boldsymbol{d}$ can vary due to asymmetry $\boldsymbol{A}$ for the relative movement between the orbiter and assets and due to jitter $\boldsymbol{J}$ of the physical medium

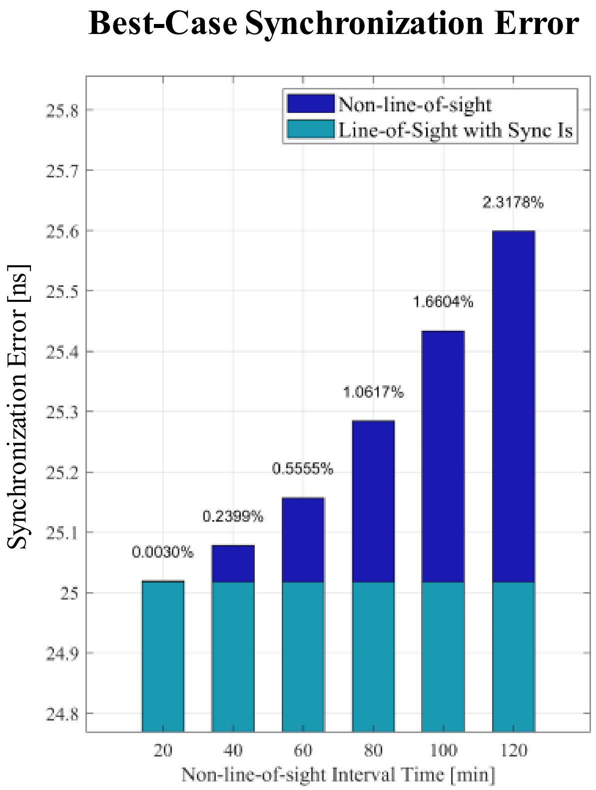
The upper bound synchronization error depends on the relative drift between the grandmaster and the asset and the wrong estimation of the grandmaster clock $P_i^U = (|\rho_i| + |\rho_{GM}|)I_s + \delta C_{i-1}^U + \delta D_i^U + g_{GM}$





Synchronization error evaluation results





Mean best and worst synchronization error considering $7.2 \cdot 10^6$ cases

$d_{\min}$ and A are evaluated for an earth orbiter at an altitude ranging from 200-600 km

J was considered variable between 0 and 50 ns

$I_s = 0.125s$ and $I_p = 1s$

$Daily\ drift_{HP-RTC} = 5 \cdot 10^{-16}$ s/day
$Clock\ Resolution_{HP-RTC} = 1\ ps$

$Daily\ drift_{RTC} = 1 \cdot 10^{-12}$ s/day
$Clock\ Resolution_{RTC} = 100\ ps$

Conclusions

TSN - MRR-BASED PASSIVE OPTICAL COMMUNICATION

In the **exploration** of **TSN integration** with **MRR-based passive optical communication** a **hybrid onboard satellite network** has been defined and proposed

INTEGRATION OF IEEE802.1AS SYNC PROTOCOL

The integration of the **IEEE802.1AS synchronization protocol** has been considered and **defined** for the scenario, and the **synchronization error evaluation** has been **performed even in non-line-of-sight conditions**

FUTURE DEVELOPMENTS

Assessment of the **impact** of **synchronization on exchanged traffic and experimental testing**

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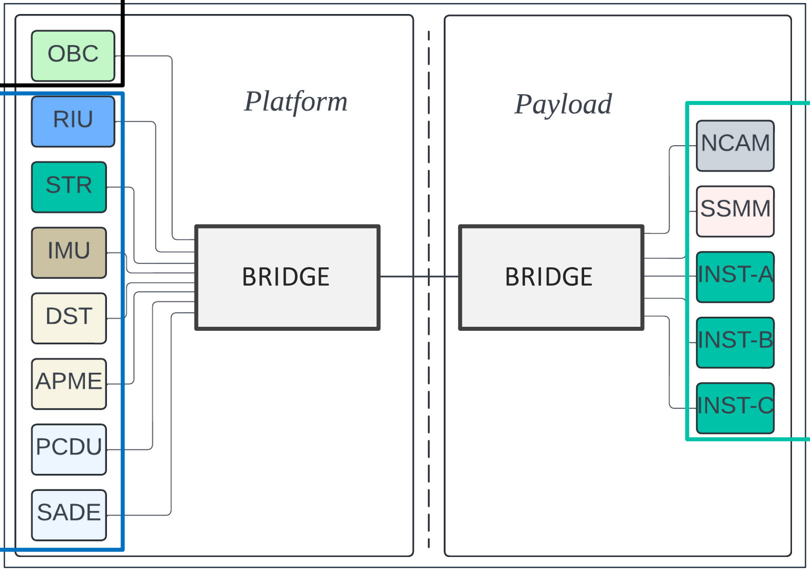
Appendix

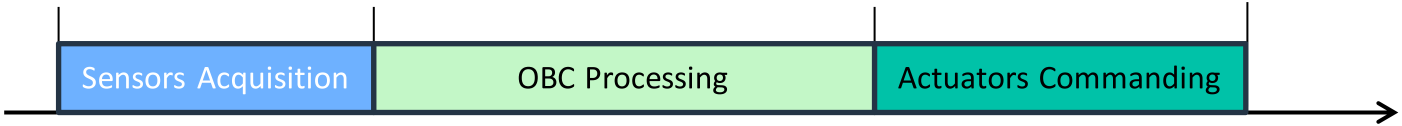
Satellite onboard network and requirements

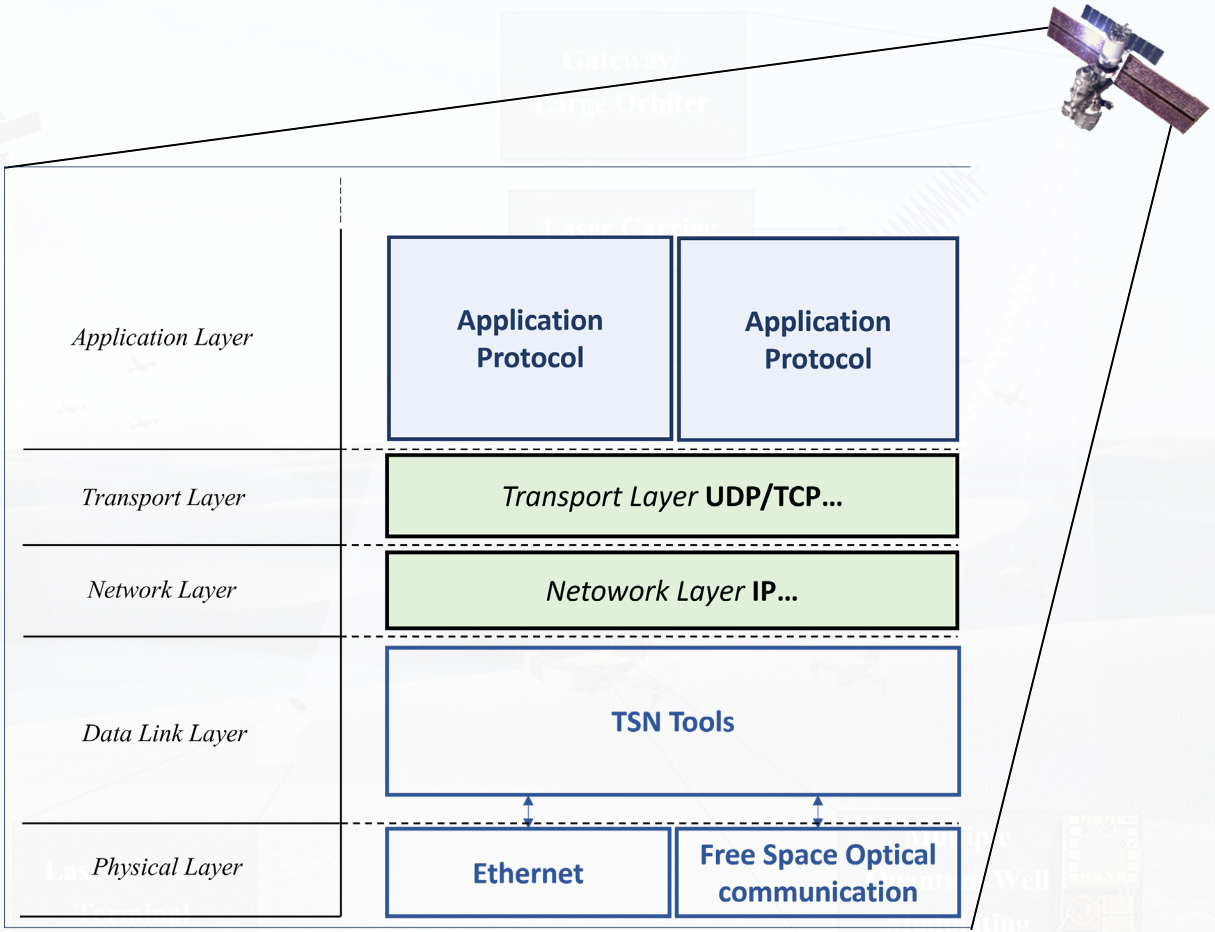
Computing End System
OBC (On-Board Computer)

Sensing/Actuating End Systems
RIU (Remote Interface Unit)
STR (Star Tracker)
IMU (Inertial Measurement Unit)
DST (Digital Satellite Terminal)
APME (Antenna Pointing Monitoring Equipment)
PCDU (Power Control Distribution Unit)
SADE (Satellite Attitude Determination Estimation)



Payload End Systems
NCAM (Navigation Camera)
SSMM (Mass Memory)
INST-A (Instrument 1)
INST-B (Instrument 2)
INST C (Instrument 3)





- **Hybrid orbiter TSN architecture** that includes **wired** and **wireless** interfaces, **enabling TSN tools** for **both wired and Free Space Optical** (FSO) **communication channels** with **MRR-based technology**

- **Onboard devices synchronize** using the **IEEE 802.1AS** protocol achieving bounded latency and minimal jitter

Time Synchronization over MRR-based passive optical communication
IEEE802.1AS