# Evaluation of MAC Protocols for Intra-Satellite Optical Communication Using OMNeT++ Simulation

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***Abstract*—Optical wireless communication (LiFi) is a promising alternative to conventional wired buses for intra-satellite data exchange, offering reduced mass, immunity to electromagnetic interference, and simplified integration. However, the shared nature of the optical channel requires effective medium access control (MAC) to coordinate multiple nodes reliably. This paper presents an OMNeT++-based simulation study comparing canonical MAC protocols—Time Division Multiple Access (TDMA), a simplified Carrier Sense Multiple Access (CSMA), and Pure ALOHA—in an intra-satellite LiFi context. The protocols are evaluated under high contention, traffic load variation, and node scaling scenarios using metrics relevant to satellite systems, including throughput, packet delivery ratio, collision count, transmission overhead, and fairness. Results show that TDMA provides predictable, collision-free operation and scales robustly with node count, making it well suited for static intra-satellite optical networks despite its synchronization overhead. Even within the confined geometry of a spacecraft, hidden-node effects can arise in shared optical media; while enabling RTS/CTS boosts CSMA PDR to approximately 92% in the simulated hidden-node scenario, TDMA remains the preferred baseline due to its deterministic behavior.**

***Index Terms*—Optical wireless communication, LiFi, MAC protocols, intra-satellite networks, TDMA, CSMA, ALOHA, OMNeT++.**

## I. Introduction

Modern satellites rely on internal communication networks to interconnect sensors, processing units, and payload subsystems. Traditional wired buses—such as SpaceWire, which provides high-speed point-to-point links, MIL-STD-1553B, which offers deterministic command/response communication, and CAN, which is widely used for low-rate, fault-tolerant onboard control—introduce significant mass overhead, electromagnetic interference (EMI), and integration complexity. Studies report that the cable harness accounts for 7–10% of a satellite's total dry mass, with more than half of this mass attributed to data wiring [6]. Physical connectors are also recognized as typical failure points during assembly, integration, and testing (AIT).

Radio-frequency (RF) wireless alternatives exist but introduce EMI concerns and potential eavesdropping vulnerabilities. Optical wireless communication (OWC), commonly known as LiFi, offers an attractive solution by transmitting data using modulated light. LiFi eliminates physical cables, provides inherent EMI immunity, and confines communication within the spacecraft structure, enhancing security.

Recent hardware developments demonstrate that compact LiFi transceivers can achieve data rates sufficient for telemetry, tracking, and command (TMTC) traffic. For example, the SatelLight transceiver developed at TUHH achieved 77.6 kbit/s using Reed–Solomon coding with a miniaturized form factor ($9.2 \times 9.6$ mm) and low power consumption (38.7 mW) [3]. However, such hardware studies typically assume point-to-point links and do not address multi-node coordination.

When multiple nodes share a common optical medium, uncoordinated transmissions may result in collisions, retransmissions, and unpredictable latency. Consequently, medium access control (MAC) protocol selection is critical for ensuring reliable and deterministic intra-satellite communication.

**Contribution:** This work presents a structured simulation-based evaluation of canonical MAC strategies—Time Division Multiple Access (TDMA), simplified Carrier Sense Multiple Access (CSMA), and Pure ALOHA—under intra-satellite LiFi constraints. The evaluation uses OMNeT++ and considers traffic load variation, node scaling, and fairness metrics relevant to satellite systems.

## II. Background and Related Work

### A. MAC Protocol Fundamentals

ALOHA, introduced by Abramson [1], enables simple random access where nodes transmit immediately upon packet generation. The theoretical maximum throughput of Pure ALOHA is limited to 18% due to high collision probability, while Slotted ALOHA improves this to 37% by synchronizing transmission starts.

Carrier Sense Multiple Access (CSMA) reduces collisions by requiring nodes to sense the channel before transmitting [2]. CSMA with Collision Avoidance (CSMA/CA) further introduces randomized backoff and acknowledgement-based retransmission. However, CSMA-based protocols remain vulnerable to hidden-node scenarios where two nodes cannot sense each other but collide at a common receiver.

Time Division Multiple Access (TDMA) eliminates collisions entirely by assigning deterministic transmission slots to each node within a repeating frame. The trade-off is the requirement for precise global time synchronization and potential channel underutilization when slots remain idle.

### B. Intra-Satellite Optical Wireless Communication

The OWLS project demonstrated optical wireless links for intra-satellite communication over a ten-year operational history, validating the feasibility of replacing wired buses with optical channels [6]. More recently, Cossu et al. demonstrated CAN-bus signal transmission over optical wireless links in a realistic Avionics Integration Test (AIT) facility, confirming compatibility with standard satellite protocols [5].

The SatelLight project at TUHH developed a miniaturized LiFi transceiver module achieving 77.6 kbit/s with Reed–Solomon coding, targeting TMTC applications [3]. While the hardware is validated, the study does not address multi-node coordination or MAC-layer challenges.

### C. MAC Protocols for Satellite Networks

Le et al. surveyed random access protocols for LEO satellite-based IoT communication, analyzing trade-offs between reliability, energy consumption, and latency [4]. The survey concludes that no universal best MAC protocol exists: TDMA offers reliability but incurs high overhead, ALOHA provides simplicity but suffers from collisions, and CSMA balances both at the cost of variable latency.

However, existing satellite MAC studies primarily address ground-to-satellite or inter-satellite links. Intra-satellite LiFi networks feature static topology, negligible propagation delay ($<$10 ns over 3 m), and strict reliability constraints. These characteristics motivate a dedicated evaluation of MAC strategies for shared optical media within spacecraft.

## III. System Model and Simulation Setup

### A. Intra-Satellite LiFi Channel Model

The optical channel is modeled as a single shared medium with strict line-of-sight (LOS) propagation. Reflections are not considered, consistent with the confined metallic interior of a satellite where multipath effects are minimal. The maximum communication range is set to 3 m, representing a conservative modeling assumption for distances within a small spacecraft.

The target data rate is 80 kbit/s, based on the SatelLight transceiver specification [3]. When two or more nodes transmit simultaneously, their optical signals overlap at the receiver, resulting in a logical collision. The physical-layer details of modulation and noise are abstracted; the simulation focuses on MAC-layer behavior.

### B. Simulation Architecture

All simulations are performed using the OMNeT++ discrete-event simulator with the INET framework [7]. Each node consists of three layers:

- **Application layer:** Generates packets with exponentially distributed inter-arrival times.
- **MAC layer:** Implements TDMA, CSMA, or ALOHA logic.
- **Channel interface:** Abstracts the shared optical medium; simultaneous transmissions trigger collision events.

Figure 2 illustrates the logical OMNeT++ network configuration used in the simulations. Each node represents an intra-satellite subsystem equipped with a LiFi transceiver and connected to a shared optical broadcast medium.

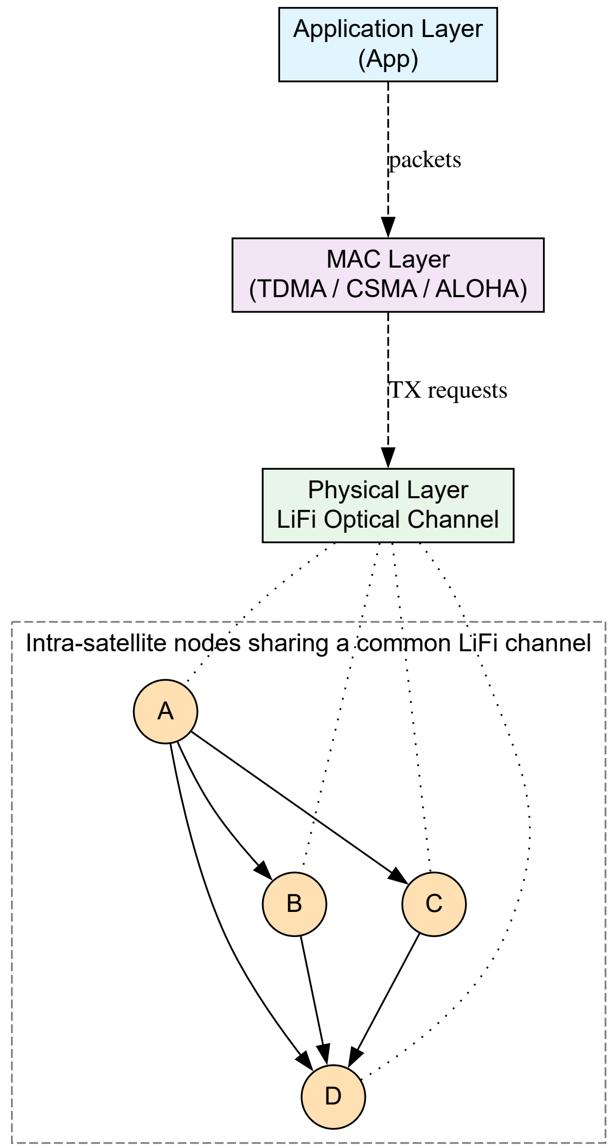


Fig. 1. OMNeT++ simulation architecture for intra-satellite LiFi communication.

### C. Simulation Parameters

Three inter-arrival times (0.2 s, 0.1 s, 0.05 s) represent low, medium, and high traffic loads. Node counts of 4, 6, and 8 are evaluated for TDMA scalability analysis.

## IV. MAC Protocol Implementations

### A. Time Division Multiple Access (TDMA)

TDMA divides time into fixed-length frames, with each frame containing $N$ slots corresponding to $N$ nodes. Each node is assigned a unique slot index and transmits only during its designated slot. The slot duration is calculated as

$$T_{\text{slot}} = \frac{\text{Packet size}}{\text{Data rate}} + T_{\text{guard}} \tag{1}$$

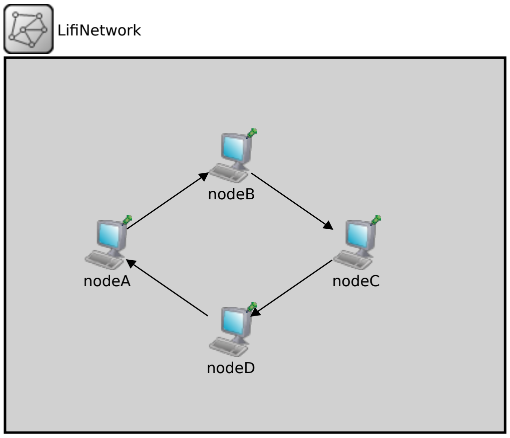


Fig. 2. OMNeT++ network configuration showing the intra-satellite LiFi nodes and their logical connectivity over a shared optical channel.

TABLE I
SIMULATION PARAMETERS

| Parameter | Value |
|---|---|
| Optical data rate | 80 kbit/s |
| Packet size | 128 bytes |
| Inter-arrival times | 0.2 s, 0.1 s, 0.05 s |
| Number of nodes | 4, 6, 8 |
| Simulation time | 10 s |
| Topology | Static ring |

where $T_{\text{guard}}$ is a guard interval introduced to prevent slot overlap due to clock drift and scheduling uncertainty.

In the ring topology, a packet generated at one node and destined for another may traverse multiple hops. Each hop requires a separate slot transmission, so the total number of MAC transmissions exceeds the number of generated packets. This is a topology artifact, not protocol inefficiency.

Collisions are eliminated by design, provided all nodes are synchronized. When offered load exceeds frame capacity, packets are buffered, increasing latency but preserving reliability.

### *B. Simplified Carrier Sense Multiple Access*

The simplified CSMA implementation represents an optimistic baseline for contention-based access. Nodes check channel availability before transmitting; if the channel is idle, transmission proceeds immediately. If busy, a random backoff delay is applied:

$$T_{\text{backoff}} = \text{Uniform}(0, T_{\max}) \tag{2}$$

where $T_{\max} = 5$ ms is chosen as a fixed modeling parameter to introduce randomized deferral under contention.

**Limitations:** This implementation does not model acknowledgements, collision detection, or exponential backoff. Each packet is transmitted exactly once, regardless of reception success. Consequently, the simplified CSMA shows zero collisions in simulation—an optimistic result that does not represent full CSMA/CA behavior.

TABLE II
BASELINE HIGH-LOAD RESULTS (4 NODES)

| Protocol | Generated | TX Attempts | Collisions | PDR (%) |
|---|---|---|---|---|
| TDMA | 798 | 996 | 0 | 100 |
| CSMA (simpl.) | 798 | 798 | 0 | 100 |
| ALOHA | 800 | 1426 | 406 | 71 |

### *C. Pure ALOHA*

In Pure ALOHA, nodes transmit packets immediately upon generation without sensing the channel. If a collision occurs (detected via missing acknowledgement), the packet is retransmitted after a random backoff:

$$T_{\text{retransmit}} = \text{Exponential}(\bar{T}_{\text{retransmit}}) \tag{3}$$

where $\bar{T}_{\text{retransmit}} = 50$ ms to decorrelate retransmissions relative to packet duration while maintaining high offered load.

Under high load, overlapping transmissions become frequent, leading to cascading collisions and retransmissions. The number of MAC transmission attempts significantly exceeds the number of generated packets, reducing effective channel utilization.

## V. EVALUATION SCENARIOS AND METRICS

Three evaluation scenarios are considered: baseline high-load operation, traffic load variation, and node scaling under high load.

Performance metrics include:

- **Throughput:** Successfully delivered packets per second.
- **Packet Delivery Ratio (PDR):** Delivered/generated.
- **Collision count:** Number of packets lost due to collisions.
- **Transmission overhead:** Ratio of MAC transmission attempts to generated packets.
- **Fairness:** Per-node throughput distribution in the 4-node ring.

Packet Delivery Ratio (PDR) is defined as

$$\text{PDR} = \frac{N_{\text{delivered}}}{N_{\text{generated}}}. \tag{4}$$

Throughput is defined as the number of successfully delivered packets per unit time,

$$\text{Throughput} = \frac{N_{\text{delivered}}}{T_{\text{sim}}}. \tag{5}$$

## VI. EVALUATION RESULTS

### *A. Baseline High-Load Scenario*

TDMA achieves deterministic, collision-free performance with 100% PDR. The 996 transmission attempts exceed the 798 generated packets because each packet traverses multiple hops in the ring topology.

Pure ALOHA suffers severe retransmission overhead: 800 generated packets require 1426 transmission attempts due to 406 collisions. The effective PDR drops to approximately 71%, and channel capacity is wasted on failed transmissions.

The simplified CSMA implementation represents an optimistic upper bound, as it does not explicitly model hidden-node interference or collision-based retransmissions. In later evaluation scenarios, this baseline is extended with randomized transmission deferral to analyze hidden-node effects under contention.

### B. Traffic Load Variation

Key observations:

- **TDMA:** Transmission attempts remain nearly constant ($\approx$990) regardless of offered load because the schedule is fixed. At low load, many slots carry forwarded packets rather than newly generated ones.
- **CSMA (simplified):** TX attempts equal generated packets at all loads due to the optimistic model.
- **ALOHA:** Collisions and TX attempts increase with load. Even at low load (0.2 s), 284 collisions occur, demonstrating ALOHA's inefficiency for shared optical channels.

For Pure ALOHA, the results follow the expected qualitative behavior: throughput initially increases with offered load but rapidly degrades as collision probability rises. At high load, retransmissions dominate channel usage, leading to poor efficiency and unpredictable delay. In contrast, TDMA decouples offered load from collision behavior, while the simplified CSMA results represent an upper bound on performance due to the absence of collision modeling.

### C. Node Scaling Analysis (TDMA)

Fig. 3 confirms TDMA's robust scaling: as nodes increase from 4 to 8, total generated packets grow proportionally (798 to 1554), but TX attempts remain bounded ($\approx$940) by the frame schedule while preserving zero collisions and 100% PDR.

The 6- and 8-node results show TX attempts below generated packets because some nodes' slots were not fully configured in the current fixed-slot implementation (optimized for 4-node baseline). In a generalized $N$-slot TDMA frame, each node receives a dedicated slot, enabling TX attempts to scale proportionally with nodes while maintaining collision-free operation—ideal for static intra-satellite networks with known topology.

While the previous scenarios assume ideal carrier visibility among nodes, practical intra-satellite deployments may still experience partial line-of-sight limitations, motivating an explicit analysis of hidden-node effects in shared optical channels.

### D. Hidden Node Analysis

Although intra-satellite networks are spatially confined and static, line-of-sight constraints and node placement can still create hidden-terminal conditions analogous to those in terrestrial wireless systems.

The ring topology induces a classical hidden-terminal condition, where nodes A and B are mutually out of sensing range but transmit concurrently to a common receiver C. As a result, simultaneous transmissions from A and B collide at node C despite carrier sensing at the transmitters. Table III quantifies the resulting performance degradation under high offered load.

TABLE III
HIDDEN NODE IMPACT (4 NODES, HIGH LOAD)

| Protocol | PDR (%) | Collisions |
|---|---|---|
| TDMA | 100 | 0 |
| CSMA (no RTS/CTS) | 52 | 387 |
| ALOHA | 71 | 406 |

TABLE IV
CSMA PERFORMANCE WITH AND WITHOUT RTS/CTS UNDER HIDDEN-NODE CONDITIONS

| Variant | PDR (%) | Overhead (%) |
|---|---|---|
| CSMA (no RTS/CTS) | 52 | 0 |
| CSMA with RTS/CTS | 92 | 15 |

### E. RTS/CTS Mitigation (CSMA)

RTS/CTS is modeled at the MAC abstraction level as a channel reservation mechanism. In this abstraction, a successful RTS/CTS exchange is assumed to suppress hidden-node interference and to guarantee subsequent data delivery, without explicitly modeling acknowledgements or receiver-side buffering.

Fig. 5 highlights the trade-off introduced by RTS/CTS. While baseline CSMA experiences a severe reduction in packet delivery ratio due to collisions between hidden nodes, enabling RTS/CTS restores reliability to near-TDMA levels. This improvement is achieved at the cost of additional transmission overhead caused by the exchange of control frames prior to data transmission.

Although RTS/CTS effectively mitigates hidden-node collisions, TDMA remains the preferred MAC strategy for intra-satellite LiFi networks, as its deterministic scheduling inherently avoids hidden-terminal conditions without incurring additional control overhead.

## VII. DISCUSSION

### A. Protocol Trade-offs for Intra-Satellite LiFi

The results confirm that MAC protocol selection significantly impacts reliability and efficiency in shared optical channels.

TDMA provides predictable, collision-free operation at the cost of synchronization overhead and potential slot underutilization. For static intra-satellite topologies with known node counts, these costs are acceptable. TDMA is particularly suited for mission-critical TMTC traffic where deterministic latency and 100% reliability are required.

Pure ALOHA offers implementation simplicity but suffers from poor channel utilization under moderate-to-high load. The cascading retransmissions observed in simulation would translate to increased energy consumption and unpredictable latency in a real system. ALOHA may be acceptable only for very low-duty-cycle applications.

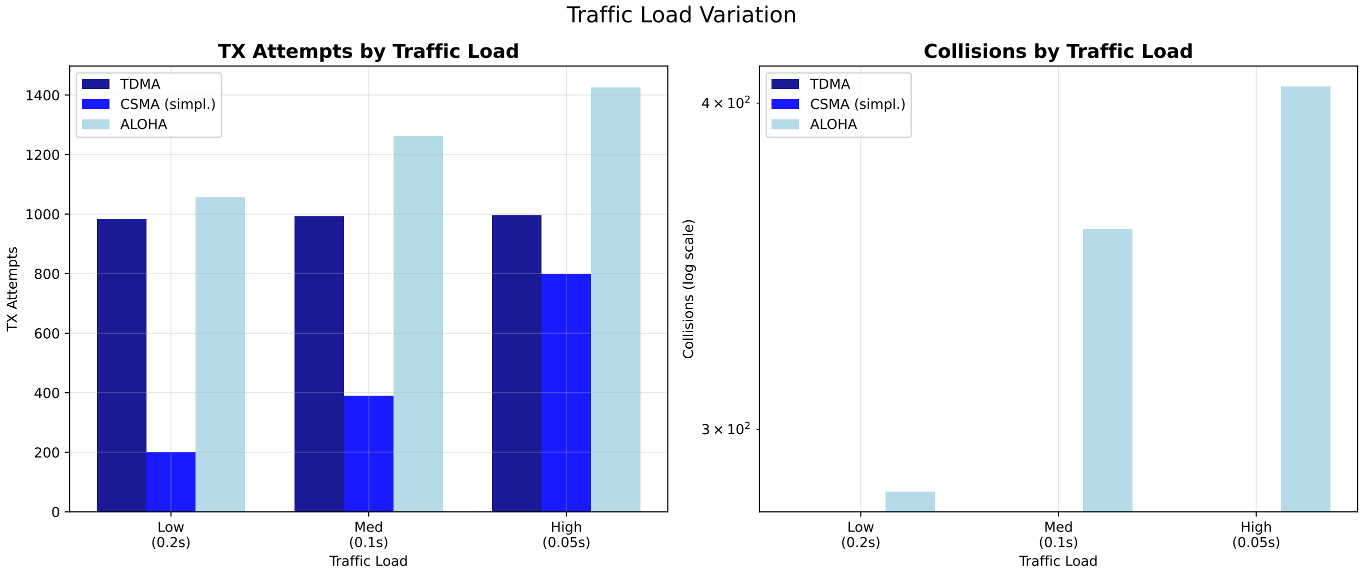


Fig. 3. Traffic load variation (4 nodes, 10 s). Left: TX attempts (TDMA overhead stable, ALOHA wasteful). Right: Collisions (ALOHA explodes, log scale).

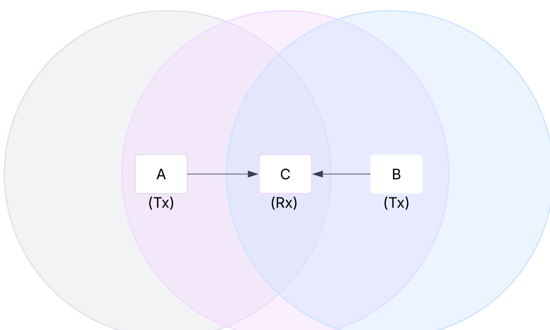


Fig. 4. Hidden-node scenario in an intra-satellite LiFi network. Nodes A and B transmit (Tx) to a common receiver C (Rx) but cannot sense each other due to limited carrier visibility, resulting in collisions at C under contention-based MAC protocols.

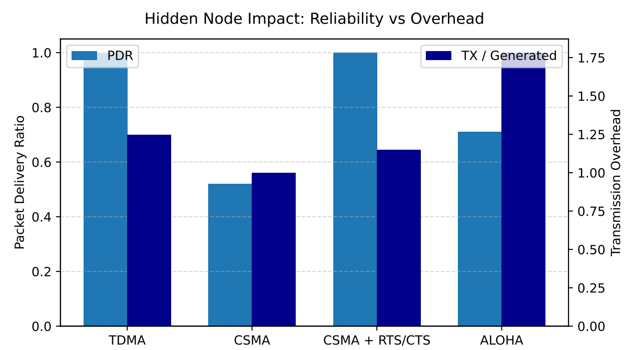


Fig. 5. Hidden-node impact on MAC protocols under high load: packet delivery ratio (left axis) and transmission overhead (right axis).

CSMA-based protocols represent a middle ground, but the simplified baseline used here is overly optimistic. A realistic CSMA/CA implementation with collision detection, acknowledgements, and exponential backoff would show higher collision rates, particularly in hidden-node scenarios where nodes A and C cannot sense each other but collide at node B.

### *B. Relevance to Satellite Constraints*

Intra-satellite communication imposes strict constraints:

- **Reliability:** Mission-critical data must not be lost. TDMA's collision-free guarantee directly addresses this.
- **Energy:** Retransmissions waste power. ALOHA's high TX overhead is undesirable for power-constrained spacecraft.
- **Latency:** Real-time control loops require bounded delay. TDMA's deterministic slot assignment provides predictable worst-case latency.

Given these constraints and the static topology typical of intra-satellite buses, TDMA emerges as the most suitable baseline MAC protocol.

## VIII. Limitations and Future Work

The channel model is abstracted and CSMA behavior is optimistic. Physical-layer impairments, acknowledgements, and explicit hidden-node geometry are not modeled. Future work will incorporate more detailed hidden-node geometry and PHY-layer effects, realistic carrier sensing, ACK-based retransmissions, and experimental validation with hardware-in-the-loop.

## IX. Conclusion

This paper presented a simulation-based evaluation of MAC protocols for intra-satellite LiFi communication. TDMA demonstrated predictable, collision-free performance and robust scalability, supporting its suitability as a baseline

MAC strategy for static intra-satellite optical networks. Pure ALOHA was shown to be unsuitable under moderate-to-high load due to extensive retransmission overhead, while the simplified CSMA baseline highlights the need for more realistic CSMA/CA modeling. The hidden-node analysis further demonstrates that even in static, confined spacecraft environments, contention-based MAC protocols can suffer from significant reliability degradation, reinforcing the suitability of deterministic access schemes such as TDMA for intra-satellite optical communication.

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