UNIVERSITY of BRADFORD

The Bradford-Renduchintala Centre for Space AI

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GÉANT

Laser Satellite-Airborne Networks for Global Connectivity

TNC25

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Laser Communications (Lasercom)

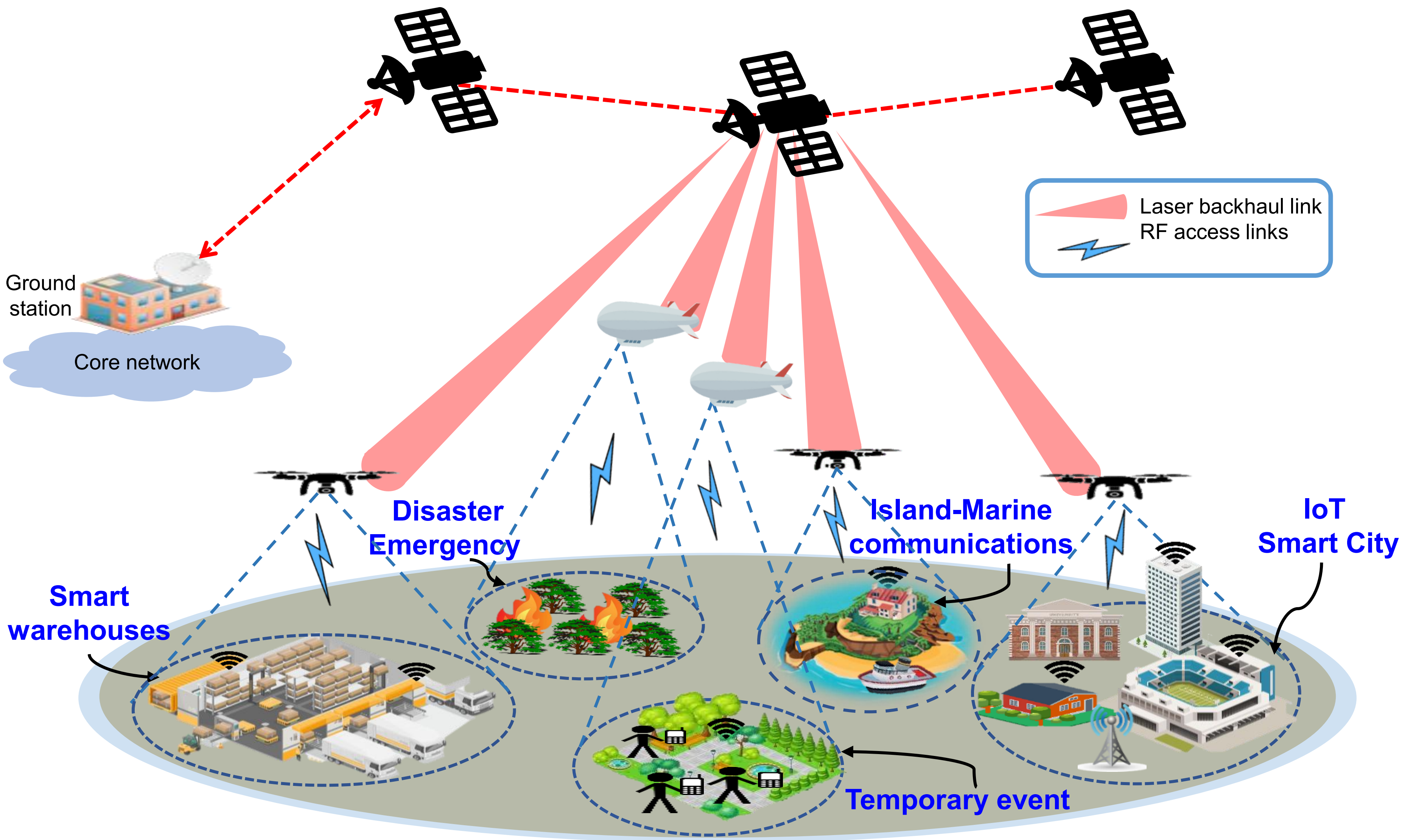
Fiber-optic technology + Wireless technology

Advantages of Lasercom over Microwave

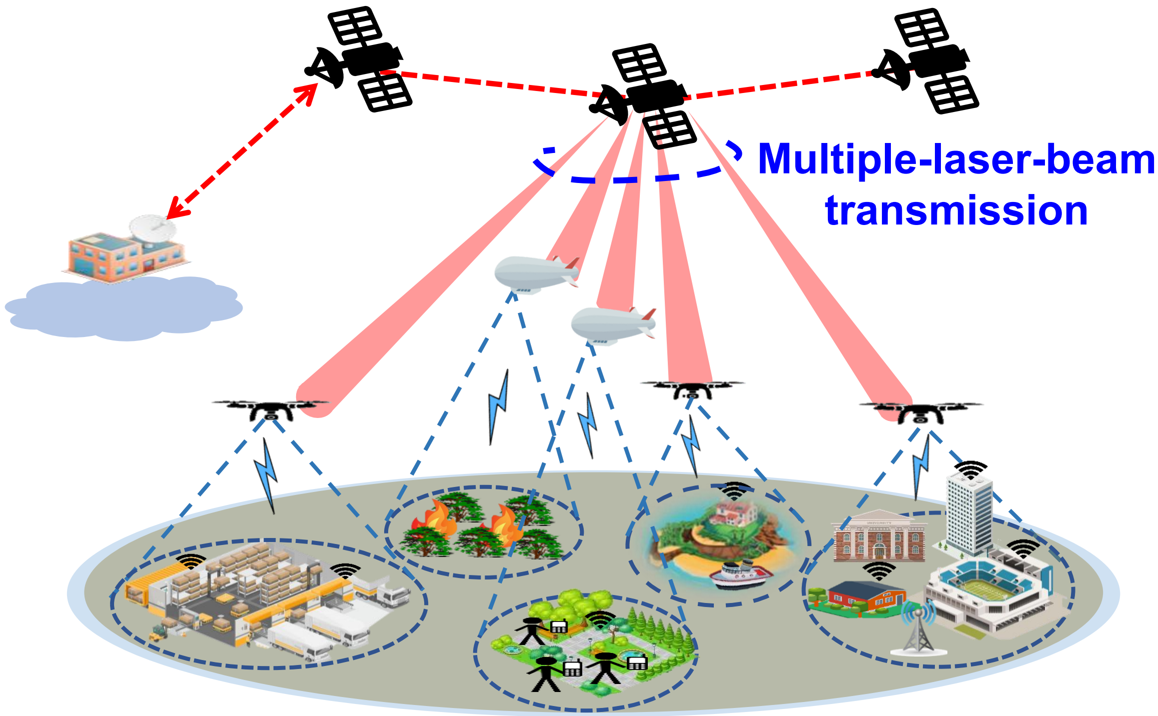
- High data rate (>1 Gbps)
- Enormous bandwidth (>100 THz)
- Unlicensed spectrum allocation
- Low power consumption (e.g., ~1/2 of microwave*)
- Small antenna size (e.g., ~1/10 of microwave*)
- Lightweight (e.g., ~1/2 of microwave*)
- No side lobes
- Good security

*H. Kaushal and G. Kaddoum, "Optical communication in space: challenges and mitigation techniques," *IEEE Comm. Sur. Tut.*, 2017.

Laser Satellite-Airborne Networks for Global Connectivity

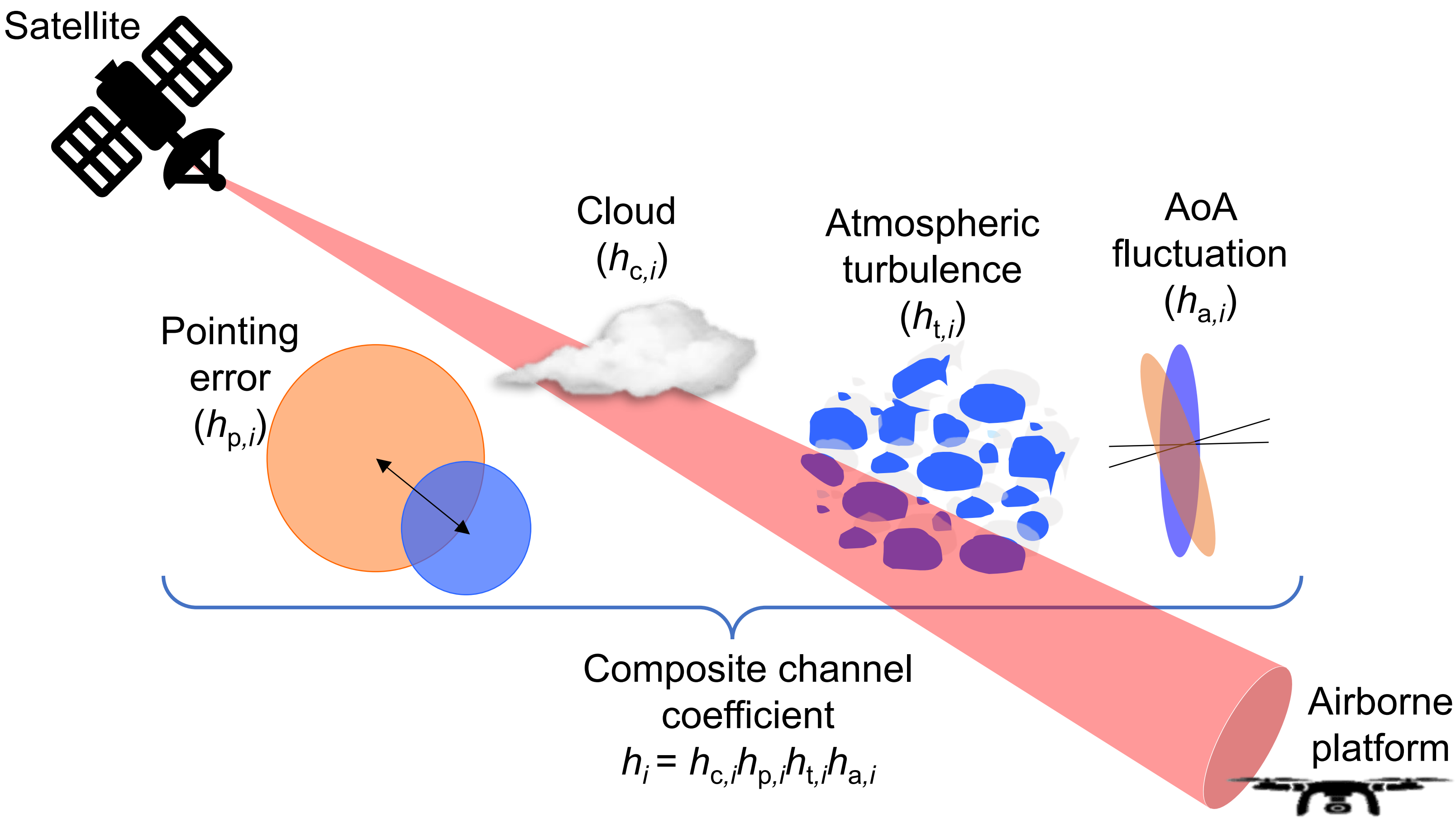


Project Innovation



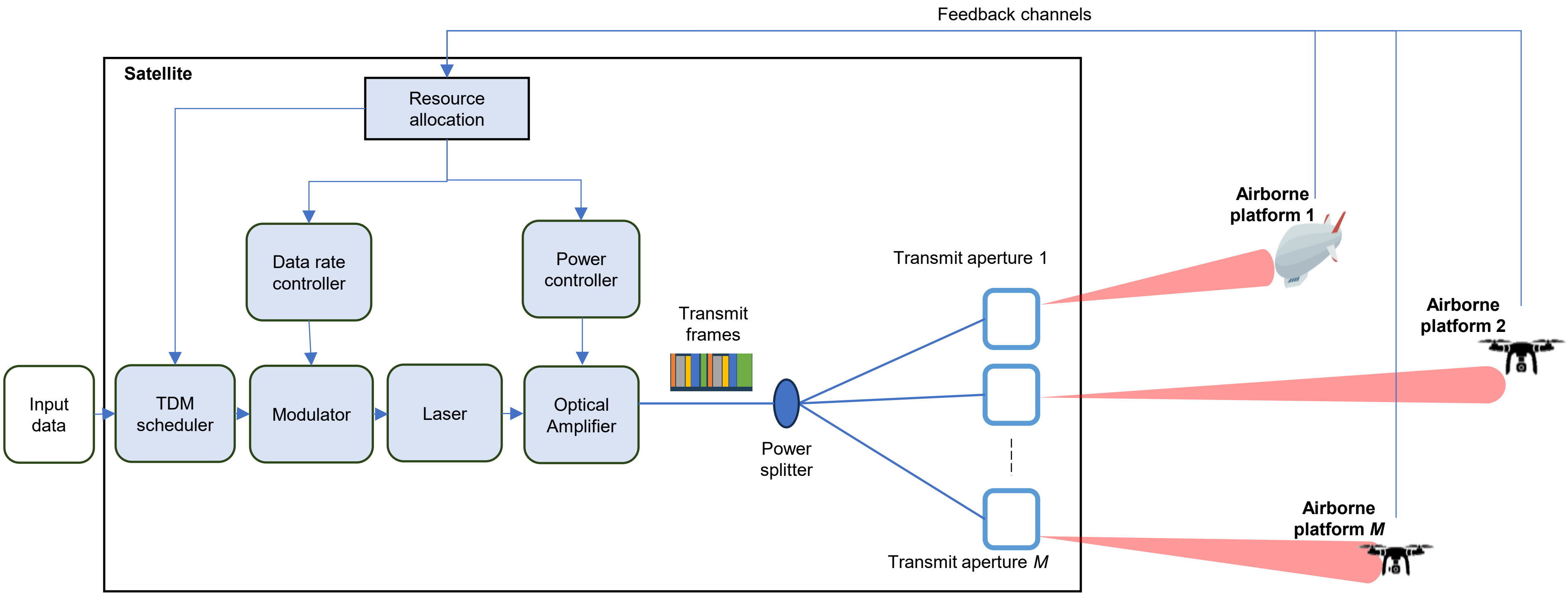
Aspect	Previous Studies / Existing Literature	Our Study
Communication Type	Ground-to-ground, satellite-to-ground, inter-airborne, or inter-satellite lasercom	Satellite-to-airborne lasercom
Communication Model	Point-to-point using a single laser beam	Point-to-multipoint using multiple laser beams
Innovation	Conventional setups with limited scalability	Novel concept enabling simultaneous connectivity for multiple airborne base stations

Our Contribution to Lasercom Study



Aspect	Previous Studies / Existing Literature	Our Study
Channel Modelling	Considered specific channel factors individually – Pointing errors and angle-of-arrival fluctuations (inter-airborne) – Atmospheric turbulence and angle-of-arrival fluctuations (satellite-to-ground)	Providing a novel channel model that integrates all these factors for laser satellite-airborne communications

Our Contribution to Lasercom Study



Aspect	Previous Studies / Existing Literature	Our Study
Backhaul Network	Studied resource allocation in conventional RF-based wireless backhaul networks	Providing data frame allocation schemes for laser satellite-airborne backhauling: – Ensuring QoS – Maintaining latency and throughput fairness – Minimizing transmitted power

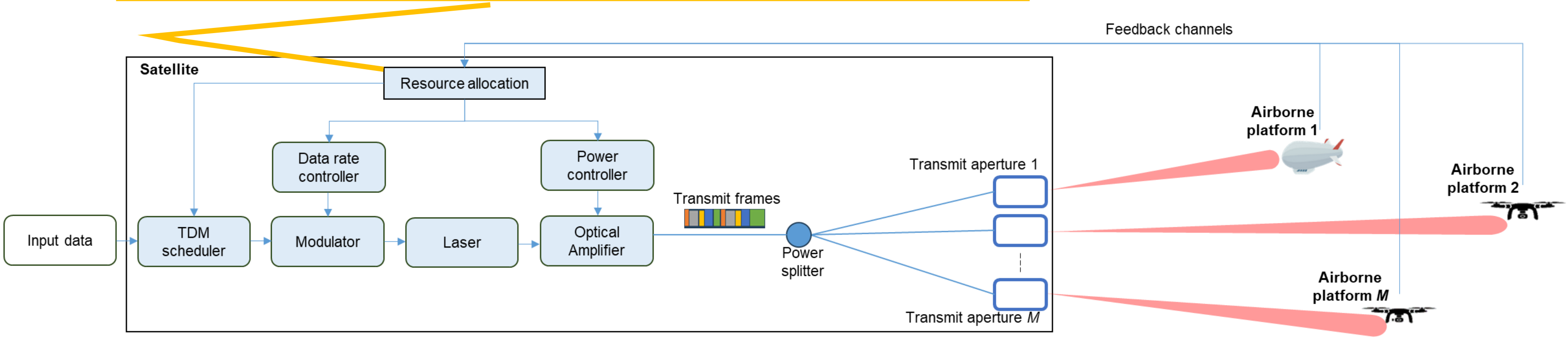
Frame Allocation
Scheme 1: Basic Rate Adaptation (BR)

$$\mathcal{H}_{k,i} = \begin{cases} \frac{\sigma_{\mathrm{n},i}}{P_{\mathrm{t},i}}\sqrt{\frac{-2}{3}(2^k-1)\ln\left(\frac{5\mathrm{FER}_{\mathrm{tar},i}}{N_{\mathrm{f}}}\right)}, & k=1,2,\cdots,K_i \\ \infty, & k=K_i+1, \end{cases}$$

(channel gain thresholds designed)

$$R_{k,i} = \begin{cases} kR_{\mathrm{s},i}, & \mathcal{H}_{k,i} \le h_i < \mathcal{H}_{k+1,i} \\ 0, & h_i < \mathcal{H}_{1,i}, \end{cases}$$

(rate adaptation)



Adaptive Data Rate	Power Management
Under BR, the data rate is determined by adjusting the modulation order according to predefined channel thresholds, enabling the system to adapt to fading without modifying power.	*BR maintains a constant power level, which can lead to suboptimal power use, especially for platforms with weaker signals or greater distance from the satellite.*

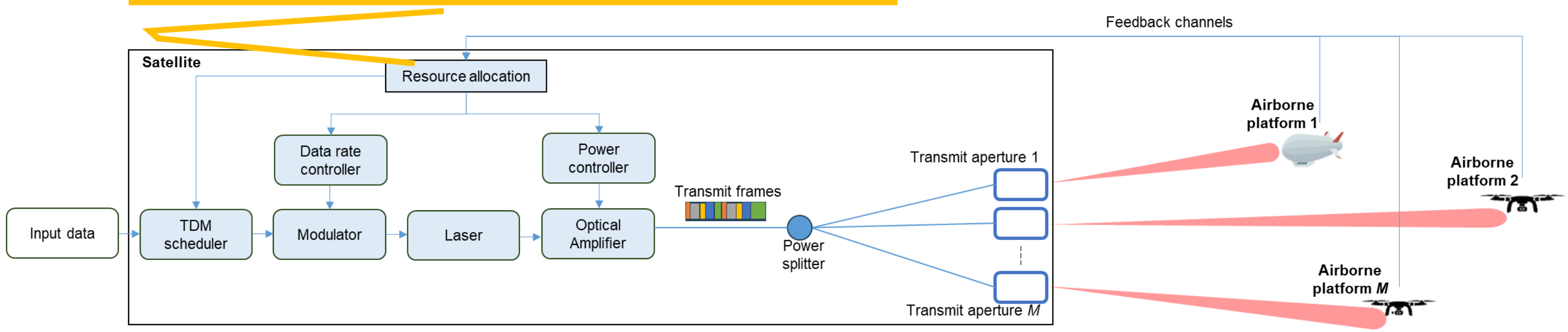
Frame Allocation
Scheme 2: Power-Constrained Rate Adaptation (PR)

$$\begin{aligned}
&\underset{\mathcal{H}_{1,i},\mathcal{H}_{2,i},\cdots,\mathcal{H}_{K_i+1,i}}{\text{minimize}} \quad P_{\mathrm{t},i} \\
&\quad\text{subject to} \\
&\qquad \mathrm{P}_{\mathrm{out},i}\left(\mathcal{H}_{1,i}\right)=\mathrm{P}_{\mathrm{tar},i}, \\
&\qquad \bar{R}_i\left(\mathcal{H}_{k,i},\mathcal{H}_{k+1,i}\right)=\bar{R}_{\mathrm{req},i}, \\
&\qquad \mathrm{FER}_{k,i}\left(\mathcal{H}_{k,i}\right)\leq \mathrm{FER}_{\mathrm{tar},i},
\end{aligned}$$

(channel gain thresholds designed)

$$R_{k,i}=\begin{cases} kR_{\mathrm{s},i}, & \mathcal{H}_{k,i}\leq h_i<\mathcal{H}_{k+1,i} \\ 0, & h_i<\mathcal{H}_{1,i}, \end{cases}$$

(rate adaptation)



Adaptive Data Rate	Power Management
PR further refines data rate adaptation by including power constraints to meet specific outage probability and average requested data rate, thus balancing data rate and power consumption.	*PR sets power constraints that balance energy consumption while maintaining specific performance metrics. This approach ensures efficient power distribution without compromising the quality of service for each platform.*

Frame Allocation Scheme 3: Dynamic Rate/Power Adaptation (DPR)

$$\begin{aligned} &\underset{\mathcal{H}_{2,i},\mathcal{H}_{3,i}\cdots,\mathcal{H}_{K_i,i}}{\text{minimize}} \quad \bar{P}_{\mathrm{t},i} = \sum_{k=1}^{K_i} \int_{\mathcal{H}_{k,i}}^{\mathcal{H}_{k+1,i}} \frac{P_{\mathrm{r},k,i} f_{h_i}(z)}{z} \mathrm{d}z \\ &\text{subject to} \\ &\qquad \mathrm{P}_{\mathrm{out},i}\left(\mathcal{H}_{1,i}\right) = \mathrm{P}_{\mathrm{tar},i}, \\ &\qquad \bar{R}_i\left(\mathcal{H}_{k,i}, \mathcal{H}_{k+1,i}\right) = \bar{R}_{\mathrm{req},i}, \\ &\qquad \mathrm{FER}_{k.i}\left(\mathcal{H}_{k.i}\right) \leq \mathrm{FER}_{\mathrm{tar},i}, \end{aligned}$$

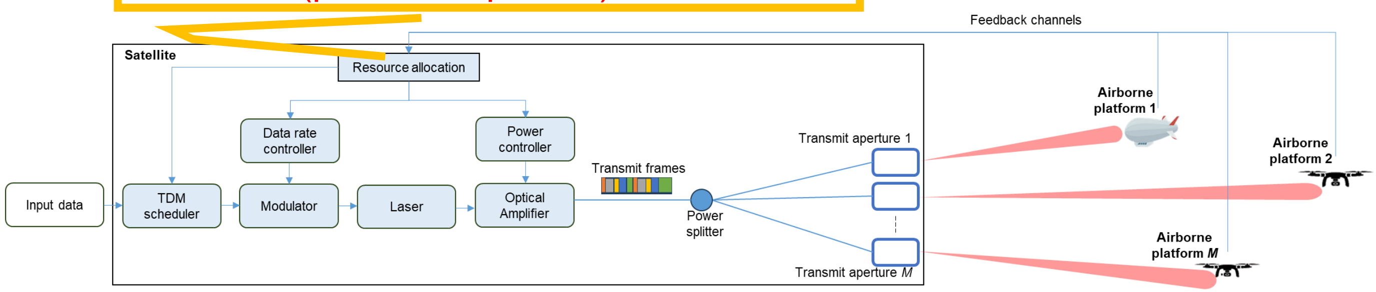
(channel gain thresholds designed)

$$R_{k,i} = \begin{cases} kR_{\mathrm{s},i}, & \mathcal{H}_{k,i} \leq h_i < \mathcal{H}_{k+1,i} \\ 0, & h_i < \mathcal{H}_{1,i}, \end{cases}$$

(rate adaptation)

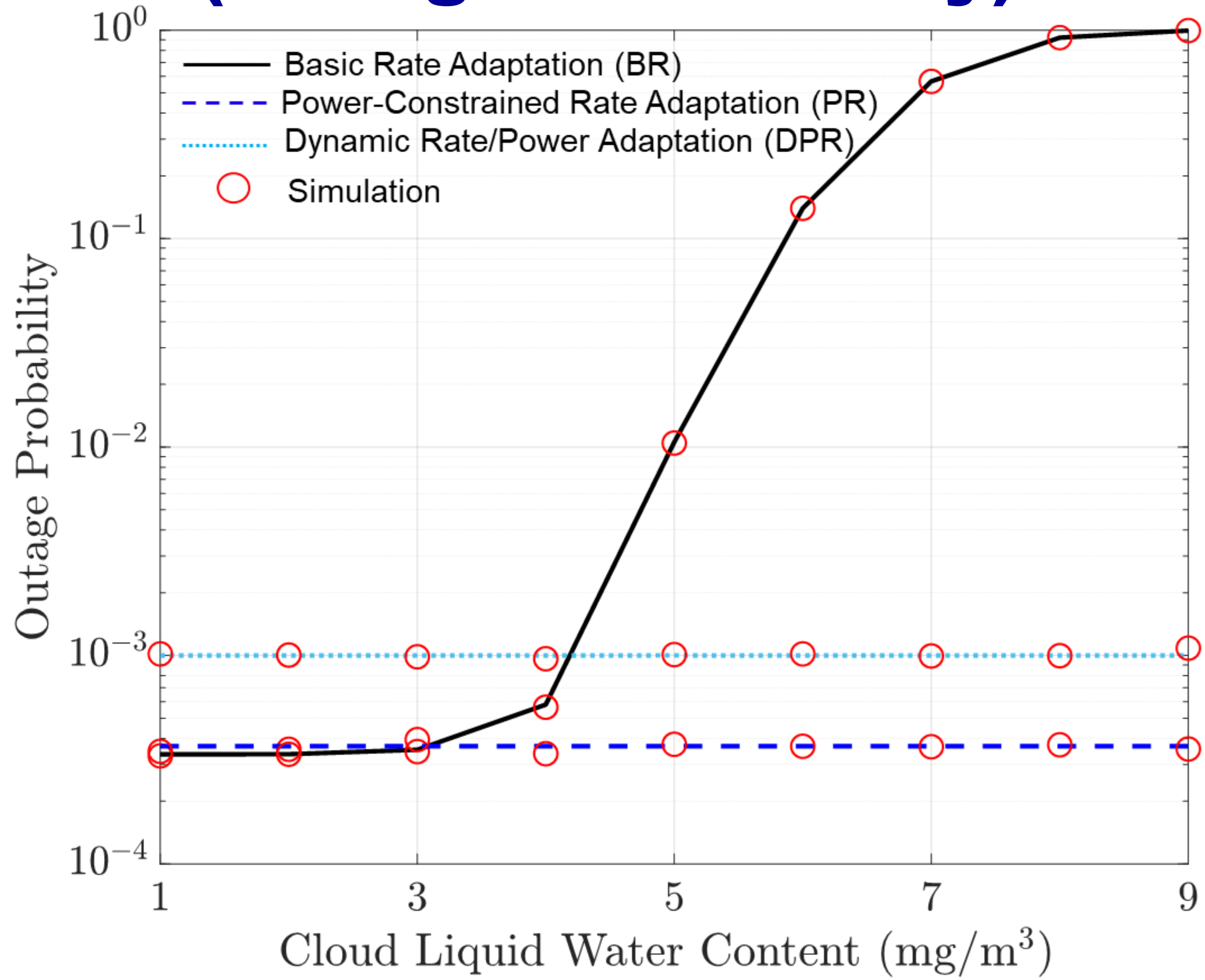
$$P_{\mathrm{t},i} = \frac{P_{\mathrm{r},k,i}}{h_i}$$

(power adaptation)

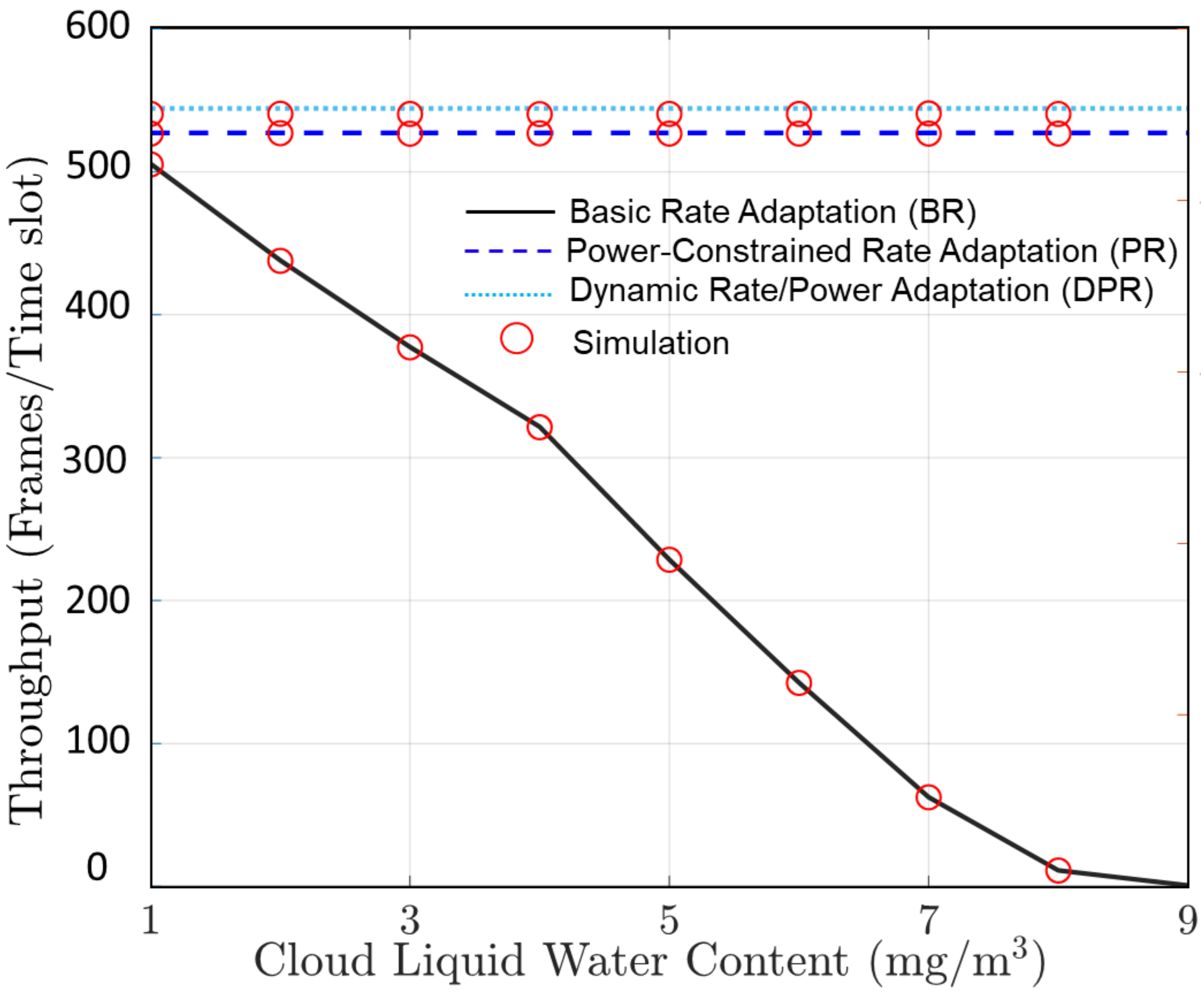


Adaptive Data Rate	Power Management
DPR dynamically adjusts both data rate and power all ocation, enabling the most flexible response to changing channel conditions. By optimizing modulation and power in real-time, DPR maintains the highest levels of data transmission reliability with minimized power usage.	DPR is the most power-efficient, dynamically adjusting power in real-time alongside modulation. This dual adaptation helps conserve energy while ensuring strong, reliable signals, especially under adverse conditions, such as atmospheric interference or significant platform distance.

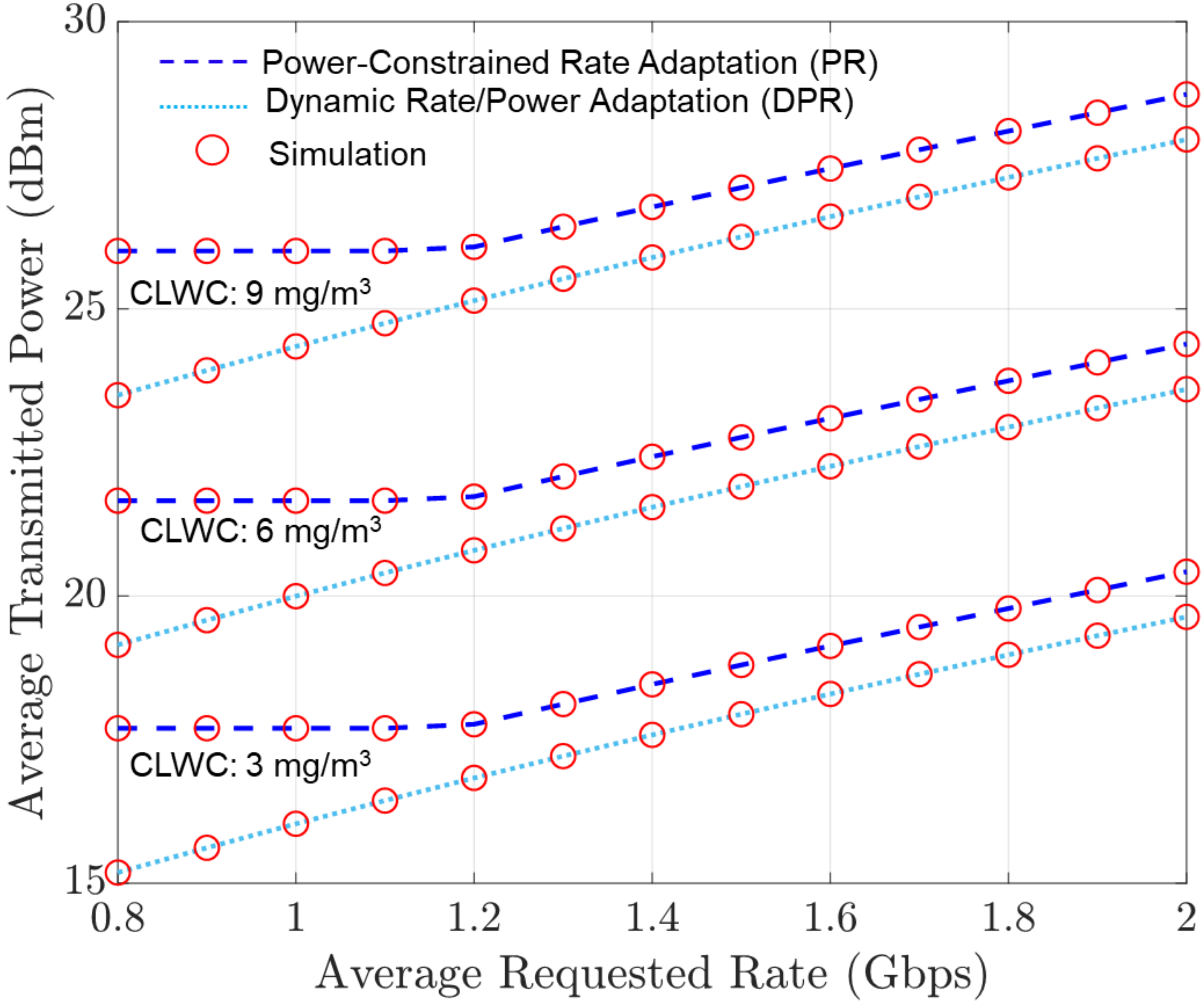
Performance Comparison (Outage Probability)



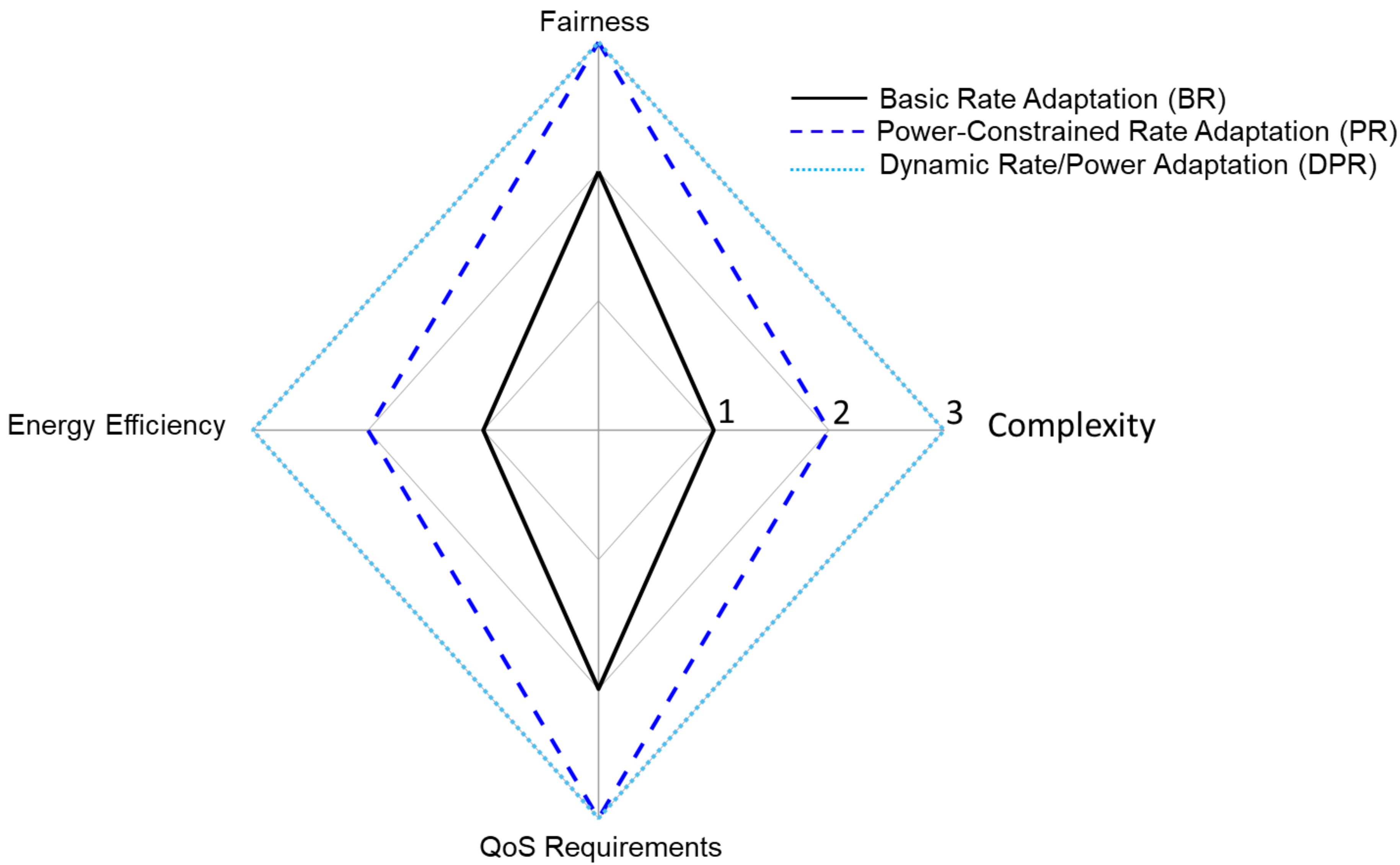
Performance Comparison (Throughput)



Performance Comparison (Transmitted Power)



Performance Comparison Summary



Summary

- ❖ Our satellite-airborne backhauling concept using multiple laser beams offers a novel solution to meet growing demands for high-speed, reliable connectivity.
- ❖ The approach supports B5G/6G, IoT, and emergency communications, enhancing future network capabilities.
- ❖ With the support of project funding, we developed a comprehensive theoretical framework for multi-beam laser satellite-airborne backhauling.
  - Channel modeling that incorporates key environmental factors
  - Efficient data allocation strategies for multiple beams
  - Analytical expressions for essential performance metrics
- ❖ This framework lays a foundation for the analysis and design of future communication networks integrating satellite and airborne components.

Thank you!

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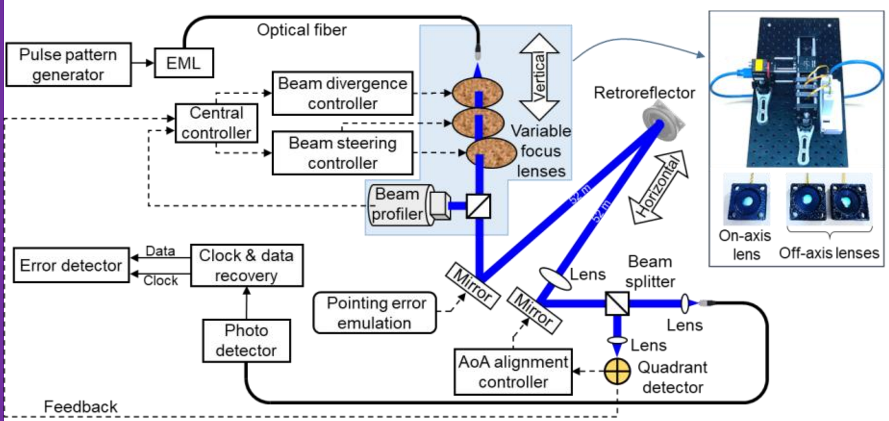
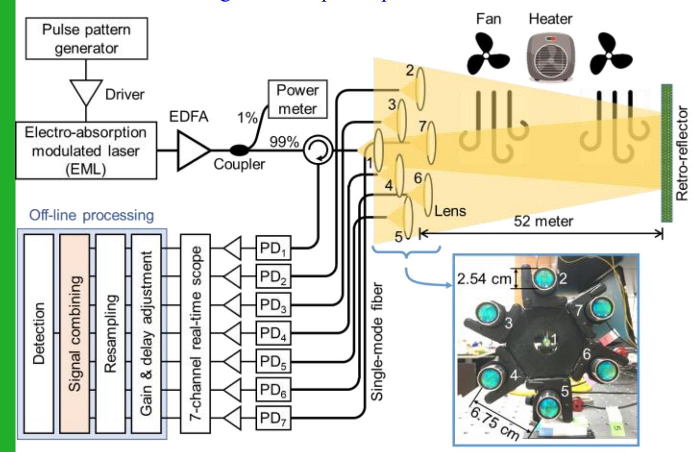
❑ Optical Beam Control and Steering

Non-mechanical Beam Steering and Adaptive Beam Control using Variable Focus Lenses for Free-Space Optical Communications



❑ Mitigation of Channel Impairments

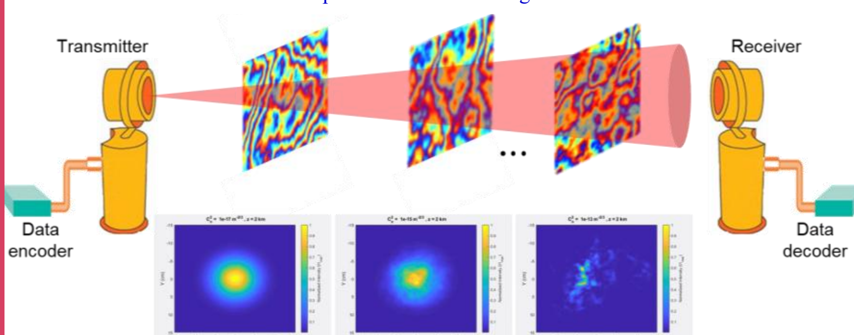
Multiple-Aperture Direct-Detection Receiver Based on Maximal Ratio Combining for Free-Space Optical Communications



Research on Lasercom

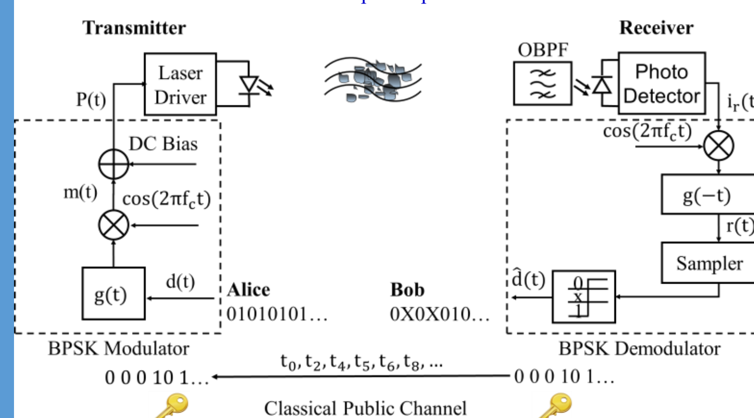
❑ Channel Modelling and System Simulation

Simulation of Free-Space Optical Communication Systems Under Atmospheric Turbulence using Phase Screens



❑ Free-Space Quantum Key Distribution

Continuous-Variable Quantum Key Distribution over Free-Space Optical Links



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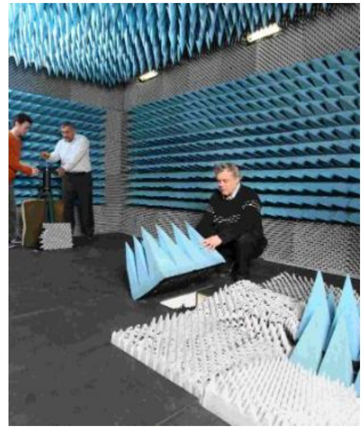
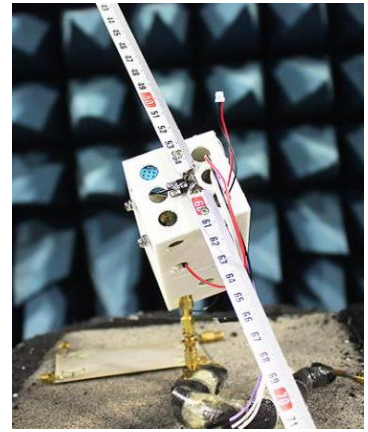
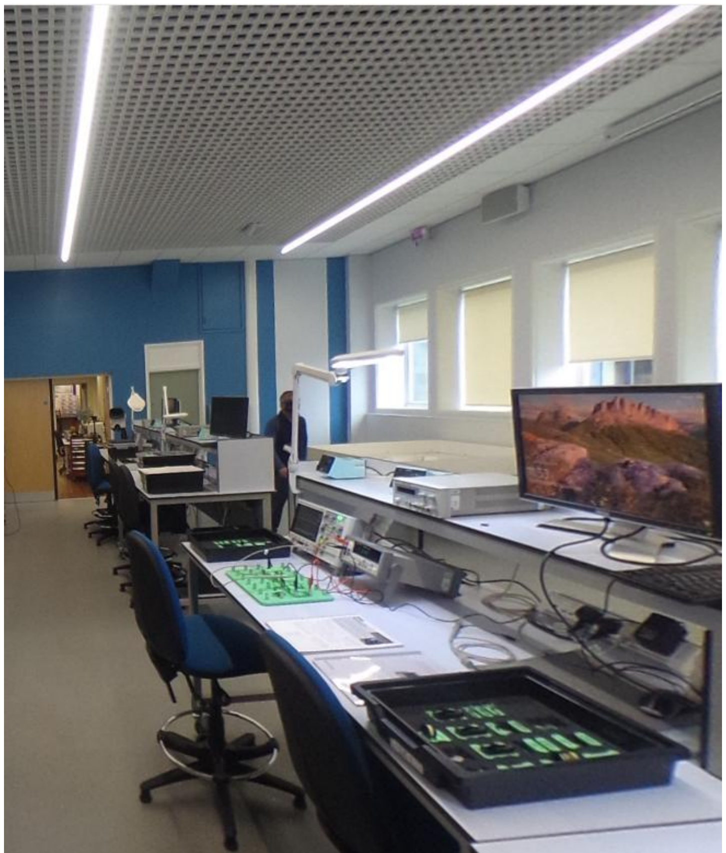
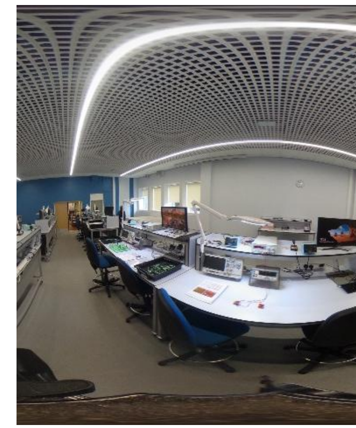






- ❑ Established in September 2021
- ❑ R&D
  - Communications
  - Earth Observation
  - Artificial Intelligence
- ❑ Educational Programmes
  - MSc Satellite Systems Engineering
  - MSc Artificial Intelligence and Space Technology
- ❑ Collaborations
  - 30 academic and research institutes over Europe through the European Satellite Network of Experts



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