

## **PhD Dissertation Title:**

# **Vertical FSO Link Modeling and Turbulence-Aware Resource Management for Enhanced Non-Terrestrial Connectivity**

### **Abstract:**

The demand for high-capacity wireless connectivity is growing very rapidly due to the exponential rise in the number of connected devices and emerging intelligent applications. Future wireless systems are expected to support massive data exchange with extremely high reliability, very low latency, and continuous network availability. To meet these stringent requirements, vertical networking architectures based on space-air-ground integrated networks (SAGIN) are being explored as a key enabler in beyond-5G and 6G technologies. Among the existing communication techniques, free-space optical (FSO) communication has emerged as a highly attractive alternative due to its very large available bandwidth, license-free operation, and immunity to electromagnetic interference.

However, unlike conventional terrestrial FSO links, vertical FSO (VFSO) channels connecting high-altitude platforms (HAPs), aerial relays, satellites, and ground receivers propagate through multiple atmospheric layers. Each atmospheric region exhibits different refractive-index fluctuation characteristics, turbulence strength, and scattering behavior. In addition, the system performance is further affected by pointing errors, beam wander, and platform dynamics. To this end, this dissertation aims at developing an analytical framework to study turbulence-driven channel behavior, system reliability, and diversity-assisted mitigation strategies in non-terrestrial optical communication systems.

As a first step, a physically consistent vertical FSO channel model is developed by incorporating altitude-dependent turbulence strength, atmospheric anisotropy, and refractive index structure variations. This model plays a key role in understanding the fundamental difference between uplink and downlink optical propagation. Unlike horizontal terrestrial links, the turbulence intensity along a vertical path is not uniform but varies sharply with altitude. Using this insight, the irradiance statistics are derived for both uplink and downlink channels, and the resulting asymmetry is quantified. It is observed that the lower atmospheric regions contribute dominantly to scintillation distortion, leading to noticeably different fading characteristics for the two propagation directions. This finding highlights the necessity of direction-aware modeling for vertical optical systems rather than relying on conventional symmetric channel assumptions.

Building upon this, a concatenated multilayer VFSO channel model is introduced to accurately capture the effect of layered turbulence along the vertical path. The propagation link is partitioned into altitude-dependent slabs, each characterized by its own turbulence parameters and fading behavior. Closed-form statistical expressions for instantaneous signal-to-noise ratio (SNR), outage probability, and average error rate are derived under weak-to-strong turbulence

conditions. These results reveal how the cumulative fading behavior is jointly governed by turbulence strength, beam wander, and pointing jitter across the layers. The developed framework aims to provide deeper physical insights into the reliability limits of HAP-to-ground and aerial relay assisted optical communication systems.

The dissertation then explores transmit diversity-based reliability enhancement strategies for turbulence dominated vertical optical links. Specifically, it investigates two practical diversity schemes, namely wavelength diversity and time diversity. The effective received signal quality and error probability are evaluated under combined turbulence and pointing error impairments. Furthermore, an asymptotic performance analysis determines the achievable diversity gain under various turbulence regimes. The study demonstrates that the relative effectiveness of the diversity schemes strongly depends on the turbulence severity. Time diversity provides notable performance improvements under strong turbulence, while wavelength diversity remains highly beneficial in moderate turbulence environments. These insights offer useful design guidelines for selecting the appropriate diversity scheme based on the operating channel conditions.

In the next part of the dissertation, turbulence-aware aerial node placement optimization is considered for vertical optical backhaul and relay networks in SAGIN frameworks. A multilayer aerial network architecture is modeled, where optical links span satellite, HAP, and ground nodes. An optimization problem is formulated to determine the optimal vertical placement of aerial relay platforms with the objective of minimizing the end-to-end outage probability. The resulting framework explicitly incorporates layered turbulence effects and pointing error statistics. Numerical results illustrate that node placement decisions significantly influence the achievable reliability and that turbulence-aware geometry selection is essential for robust link design.

The analytical findings throughout the dissertation are validated using Monte-Carlo simulation of altitude-varying turbulence channels, ensuring the accuracy and consistency of the proposed models. The results collectively emphasize that turbulence-driven impairments dominate the performance of vertical optical links and that appropriately designed diversity techniques and optimized aerial geometry can substantially enhance system reliability.

Overall, a comprehensive turbulence-aware modeling, analysis, and optimization framework for vertical FSO systems, covering channel asymmetry, concatenated fading characterization, transmit diversity enabled performance enhancement, and aerial-node placement optimization is presented. These insights are crucial for the design of reliable, high-capacity, energy-efficient, and scalable optical communication infrastructures for future non-terrestrial and 6G-ready wireless networks.