VERTICAL FSO LINK MODELING AND TURBULENCE-AWARE RESOURCE MANAGEMENT FOR ENHANCED NON-TERRESTRIAL CONNECTIVITY

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by

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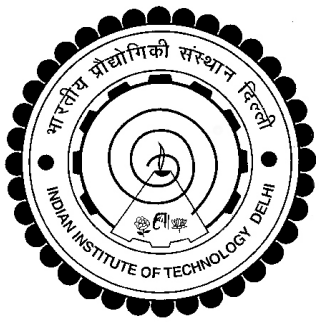

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Certificate

This is to certify that the dissertation entitled **Vertical FSO Link Modeling and Turbulence-Aware Resource Management for Enhanced Non-Terrestrial Connectivity**, submitted by **Ms. Neha Tiwari**, a Research Scholar, in the *Bharti School of Telecommunication Technology and Management*, *Indian Institute of Technology Delhi*, *New Delhi*, *India*, for the award of the degree of **Doctor of Philosophy**, is a record of an original research work carried out by her under my supervision and guidance. The dissertation fulfills all requirements as per the regulations of this Institute and in my opinion has reached the standard needed for submission. Neither this dissertation nor any part of it has been submitted for any degree or academic award elsewhere.



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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 in-

stantaneous 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.

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.

सारांश

उच्च क्षमता वाली वायरलेस संचार सेवाओं की मांग, परस्पर जुड़े उपकरणों (Connected Devices) की संख्या में तीव्र वृद्धि तथा उभरते हुए बुद्धिमान अनुप्रयोगों (Intelligent Applications) के कारण निरंतर बढ़ रही है। भविष्य की वायरलेस संचार प्रणालियों से अपेक्षा की जाती है कि वे अत्यधिक विश्वसनीयता, अत्यल्प विलंबता (Low Latency) तथा निरंतर नेटवर्क उपलब्धता के साथ विशाल मात्रा में डेटा के आदान-प्रदान का समर्थन करें। इन कठोर आवश्यकताओं की पूर्ति के लिए स्पेस-एयर-ग्राउंड इंटीग्रेटेड नेटवर्क (Space-Air-Ground Integrated Network, SAGIN) पर आधारित ऊर्ध्वाधर नेटवर्क संरचनाओं को Beyond-5G तथा 6G संचार प्रणालियों के एक महत्वपूर्ण सक्षमकारी माध्यम के रूप में विकसित किया जा रहा है। वर्तमान संचार तकनीकों में फ्री-स्पेस ऑप्टिकल (Free-Space Optical, FSO) संचार अपनी अत्यधिक उपलब्ध बैंडविड्थ, लाइसेंस-मुक्त संचालन तथा विद्युतचुंबकीय हस्तक्षेप (Electromagnetic Interference) से अप्रभावित होने के कारण एक अत्यंत प्रभावी एवं आकर्षक विकल्प के रूप में उभरकर सामने आया है।

पारंपरिक स्थलीय FSO लिंक के विपरीत, उच्च-ऊँचाई प्लेटफॉर्म (HAP), हवाई रिले, उपग्रह तथा भू-आधारित रिसीवरों को जोड़ने वाले ऊर्ध्वाधर फ्री-स्पेस ऑप्टिकल (VFSO) चैनल अनेक वायुमंडलीय परतों से होकर गुजरते हैं। प्रत्येक वायुमंडलीय परत में अपवर्तनांक के उतार-चढ़ाव की प्रकृति, वायुमंडलीय अशांति (Turbulence) की तीव्रता तथा प्रकीर्णन (Scattering) का व्यवहार भिन्न होता है। इसके अतिरिक्त, पॉइंटिंग त्रुटियों, बीम वांडर तथा प्लेटफॉर्म की गतिशीलता के कारण भी संचार प्रणाली का प्रदर्शन प्रभावित होता है। इन्हीं चुनौतियों के समाधान के उद्देश्य से, इस शोधप्रबंध में गैर-स्थलीय प्रकाशीय संचार प्रणालियों के लिए वायुमंडलीय अशांति से प्रभावित चैनल व्यवहार, प्रणाली की विश्वसनीयता तथा विविधता-आधारित प्रदर्शन सुधार तकनीकों के अध्ययन हेतु एक व्यापक विश्लेषणात्मक ढाँचा विकसित किया गया है।

प्रथम चरण में, ऊँचाई-निर्भर वायुमंडलीय अशांति की तीव्रता, वायुमंडलीय विषमदैशिकता तथा अपवर्तनांक संरचना में होने वाले परिवर्तनों को सम्मिलित करते हुए एक भौतिक रूप से सुसंगत एवं यथार्थपरक ऊर्ध्वाधर FSO चैनल मॉडल विकसित किया गया है। यह मॉडल अपलिंक तथा

डाउनलिंक प्रकाशीय प्रसार के मध्य विद्यमान मूलभूत अंतर को स्पष्ट करने में महत्वपूर्ण भूमिका निभाता है। क्षैतिज स्थलीय FSO लिंकों के विपरीत, ऊर्ध्वाधर प्रसारण पथ में वायुमंडलीय अशांति की तीव्रता समान नहीं रहती, बल्कि ऊँचाई के साथ तीव्रता से परिवर्तित होती है। इसी तथ्य के आधार पर अपलिंक तथा डाउनलिंक दोनों चैनलों के लिए विकिरण तीव्रता के सांख्यिकीय गुण प्राप्त किए गए हैं तथा उनके मध्य विद्यमान असममिति का मात्रात्मक विश्लेषण किया गया है। अध्ययन से यह स्पष्ट होता है कि वायुमंडल की निचली परतें स्किन्टिलेशन विकृति में प्रमुख योगदान देती हैं। फलस्वरूप, दोनों प्रसारण दिशाओं में फेडिंग की विशेषताएँ उल्लेखनीय रूप से भिन्न हो जाती हैं। यह निष्कर्ष दर्शाता है कि ऊर्ध्वाधर प्रकाशीय संचार प्रणालियों के लिए पारंपरिक सममित चैनल मान्यताओं पर निर्भर रहने के स्थान पर दिशा-संवेदी चैनल मॉडलिंग अपनाना आवश्यक है।

उपरोक्त मॉडल के आधार पर, ऊर्ध्वाधर प्रसारण पथ में विभिन्न वायुमंडलीय परतों में विद्यमान अशांति के प्रभाव का यथार्थ निरूपण करने के लिए एक संयोजित बहुपरत VFSO चैनल मॉडल प्रस्तुत किया गया है। इस मॉडल में संचार पथ को ऊँचाई-निर्भर अनेक परतों में विभाजित किया गया है, जहाँ प्रत्येक परत को उसके विशिष्ट वायुमंडलीय अशांति मापदण्डों तथा फेडिंग व्यवहार द्वारा निरूपित किया गया है। कमजोर से प्रबल वायुमंडलीय अशांति की परिस्थितियों में तात्कालिक SNR, आउटेज प्रायिकता तथा औसत त्रुटि दर के बंद-रूप सांख्यिकीय व्यंजक प्राप्त किए गए हैं। परिणामों से स्पष्ट होता है कि संचयी फेडिंग का व्यवहार विभिन्न वायुमंडलीय परतों में उपस्थित अशांति की तीव्रता, बीम वांडर तथा पॉइंटिंग जिटर के संयुक्त प्रभाव से नियंत्रित होता है। विकसित विश्लेषणात्मक ढाँचा HAP-से-भूमि तथा हवाई रिले-सहायित प्रकाशीय संचार प्रणालियों की विश्वसनीयता की सीमाओं के संबंध में गहन भौतिक समझ प्रदान करता है।

इसके पश्चात्, इस शोधप्रबंध में वायुमंडलीय अशांति-प्रधान ऊर्ध्वाधर प्रकाशीय लिंकों की विश्वसनीयता में वृद्धि के लिए प्रेषण विविधता पर आधारित तकनीकों का अध्ययन किया गया है। विशेष रूप से, तरंगदैर्ध्य विविधता तथा कालिक विविधता नामक दो व्यावहारिक विविधता तकनीकों का विस्तृत विश्लेषण प्रस्तुत किया गया है। संयुक्त रूप से विद्यमान वायुमंडलीय अशांति तथा पॉइंटिंग त्रुटियों के प्रभाव में प्राप्त संकेत की गुणवत्ता एवं त्रुटि प्रायिकता का मूल्यांकन किया गया है। इसके अतिरिक्त, विभिन्न वायुमंडलीय अशांति परिस्थितियों में प्राप्त किए जा सकने वाले विविधता लाभ के निर्धारण हेतु असिम्प्टोटिक प्रदर्शन विश्लेषण भी किया गया है। अध्ययन से स्पष्ट होता है कि इन विविधता तकनीकों की प्रभावशीलता मुख्यतः वायुमंडलीय अशांति की तीव्रता पर निर्भर करती है। प्रबल अशांति की स्थिति में कालिक विविधता प्रणाली के प्रदर्शन में उल्लेखनीय सुधार प्रदान करती है, जबकि मध्यम अशांति की परिस्थितियों में तरंगदैर्ध्य विविधता अधिक प्रभावी सिद्ध होती है। ये निष्कर्ष प्रचलित चैनल परिस्थितियों के अनुरूप उपयुक्त विविधता तकनीक के चयन हेतु उपयोगी अभिकल्पन दिशा-निर्देश प्रदान करते हैं।

शोधप्रबंध के अगले भाग में, SAGIN संरचना के अंतर्गत ऊर्ध्वाधर प्रकाशीय बैकहॉल तथा रिले नेटवर्कों के लिए वायुमंडलीय अशांति-संवेदी हवाई नोड स्थान-निर्धारण के अनुकूलन का अध्ययन किया गया है। इसके लिए एक बहुपरत हवाई नेटवर्क संरचना का मॉडल विकसित किया गया है,

जिसमें उपग्रह, HAP तथा भू-आधारित नोड प्रकाशीय लिंकों द्वारा परस्पर जुड़े हुए हैं। हवाई रिले प्लेटफॉर्मों की इष्टतम ऊर्ध्वाधर स्थिति निर्धारित करने हेतु एक अनुकूलन समस्या प्रतिपादित की गई है, जिसका उद्देश्य एंड-टू-एंड आउटेज प्रायिकता को न्यूनतम करना है। प्रस्तावित विश्लेषणात्मक ढाँचे में बहुपरत वायुमंडलीय अशांति के प्रभावों तथा पॉइंटिंग त्रुटियों के सांख्यिकीय गुणों को स्पष्ट रूप से सम्मिलित किया गया है। संख्यात्मक परिणाम दर्शाते हैं कि हवाई नोडों का स्थान-निर्धारण प्रणाली की प्राप्त की जा सकने वाली विश्वसनीयता को महत्वपूर्ण रूप से प्रभावित करता है तथा सुदृढ़ प्रकाशीय लिंक अभिकल्पन के लिए वायुमंडलीय अशांति-संवेदी नेटवर्क विन्यास का चयन अत्यंत आवश्यक है।

शोधप्रबंध में प्रस्तुत सभी विश्लेषणात्मक निष्कर्षों का सत्यापन ऊँचाई-निर्भर वायुमंडलीय अशांति चैनलों के मॉन्टे-कार्लो सिमुलेशन के माध्यम से किया गया है, जिससे प्रस्तावित मॉडलों की शुद्धता एवं विश्वसनीयता सुनिश्चित होती है। समग्र परिणाम यह स्पष्ट करते हैं कि ऊर्ध्वाधर प्रकाशीय लिंकों के प्रदर्शन पर वायुमंडलीय अशांति का प्रभाव सर्वाधिक प्रमुख है तथा उपयुक्त रूप से अभिकल्पित विविधता तकनीकों एवं अनुकूलित हवाई नेटवर्क संरचना के माध्यम से प्रणाली की विश्वसनीयता में उल्लेखनीय वृद्धि की जा सकती है।

अंततः, इस शोधप्रबंध में ऊर्ध्वाधर FSO प्रणालियों के लिए वायुमंडलीय अशांति-संवेदी मॉडलिंग, विश्लेषण तथा अनुकूलन का एक समग्र विश्लेषणात्मक ढाँचा प्रस्तुत किया गया है। इसमें चैनल असममिति के विश्लेषण, संयोजित फेडिंग मॉडलिंग, प्रेषण विविधता द्वारा प्रदर्शन सुधार तथा हवाई नोड स्थान-निर्धारण के अनुकूलन जैसे प्रमुख शोध योगदान सम्मिलित हैं। प्रस्तुत निष्कर्ष भविष्य के गैर-स्थलीय एवं 6G-सक्षम वायरलेस नेटवर्कों के लिए विश्वसनीय, उच्च क्षमता, ऊर्जा-कुशल तथा विस्तारयोग्य प्रकाशीय संचार अवसंरचना के अभिकल्पन एवं विकास में महत्वपूर्ण योगदान प्रदान करेंगे।

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List of Symbols

P_t	Optical transmit power
R	Link range / propagation distance
λ	Optical wavelength
η	Photodetector responsivity
σ_n^2	Noise variance
γ	Instantaneous signal-to-noise ratio (SNR)
$\bar{\gamma}$	Average SNR
I	Received optical irradiance
I_0	Normalization constant of irradiance
α, β	Gamma-Gamma fading parameters
σ_l^2	Lognormal variance parameter
σ_s^2	Scintillation index
σ_p^2	Pointing error variance
w_z	Beam spot radius at distance z
r	Radial displacement between beam and detector centre
d	Receiver aperture diameter
P_e	Average bit error probability (ABER)
P_{out}	Outage probability
C	Instantaneous channel capacity
$\mathbb{E}[\cdot]$	Expectation operator
$f_X(x)$	Probability density function (PDF) of X
$F_X(x)$	Cumulative distribution function (CDF) of X
θ	Zenith / elevation angle of the link
H	Altitude of aerial platform
R_0	Ground projection distance from platform to user
$\mathcal{L}$	Atmospheric loss / attenuation
$\mathcal{M}$	Málaga-$\mathcal{M}$ turbulence parameter
$\mathrm{Q}(\cdot)$	Gaussian Q-function

$\Gamma(\cdot)$	Gamma function
$K_\nu(\cdot)$	Modified Bessel function of the second kind
f	Frequency of transmitted optical beam from transmitter mounted on HAP
λ	Wavelength of transmitted optical beam from transmitter mounted on HAP
c	Velocity of light in vacuum
μ	Mean of a random variable
σ	Standard deviation of a random variable
$\mathbb{E}$	Expectation operator
$\mathcal{N}$	Normal distribution
A	Deployment area
d_{tx-rx}	Distance between transmitter and receiver
Ψ	Deviation in elevation angle
P_{cov}	Coverage probability

List of Abbreviations

FSO	Free-Space Optical
VFSO	Vertical Free-Space Optical
SAGIN	Space-Air-Ground Integrated Network
NTN	Non-Terrestrial Network
HAP	High Altitude Platform
tHAP	Tethered High Altitude Platform
UAV	Unmanned Aerial Vehicle
LoS	Line-of-Sight
NLoS	Non-Line-of-Sight
SNR	Signal-to-Noise Ratio
BER	Bit Error Rate
ABER	Average Bit Error Rate
PDF	Probability Density Function
CDF	Cumulative Distribution Function
AWGN	Additive White Gaussian Noise
MC	Monte-Carlo
Tx	Transmitter
Rx	Receiver
GG	Gamma-Gamma Distribution
LN	Lognormal Distribution
OAP	Optimal Aerial Placement
DF	Decode-and-Forward
AF	Amplify-and-Forward
QoS	Quality of Service
6G	Sixth-Generation Wireless