Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

# Design and Analysis of Hybrid Optical-Wireless Communication Systems for Ultra-High-Speed Networks

**Muhammad Ehtisham Ali** (Corresponding Author)
Electrical Engineering, University of Engineering and Technology, Lahore, Pakistan
Email: mea00988@gmail.com

**Emran Bilal**
Lecturer, Department of Cybersecurity, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan.
Email: imranbilal99@gmail.com

**Sadia Amjad**
Faculty of Animal Science (FAPET), Universitas Jambi, Jambi, Indonesia
Email: amjadsadia169@gmail.com

## ABSTRACT

**Background**: The explosion of data-intensive services and the need for ultra-reliable low latency communication are stretching the capabilities of traditional network infrastructures to the limit. Fiber networks can provide high capacity at a high reliability but wireless systems, such as millimeter-wave (mmWave) or free-space optical (FSO) communication systems, provide flexibility and scalability. But each of them has several weaknesses to ensure the same performance under different environmental and traffic conditions. Hybrid optical wireless networks can also be considered as a promising solution to accommodate the strengths in optical and wireless networks and thus provides an ultra-high speed, resilient and energy efficient generic network.
**Aim**: The objective of the current study was to develop and investigate a hybrid communication system model combining optical fiber, FSO, and mmWave links in order to evaluate important performance metrics such as throughput, delay, energy efficiency, BER, and link availability.
**Method**: MATLAB Simulink and NS-3 platforms were used along with a small-scale experimental setup-based approach. The Reinforcement-learning-based Dynamic Routing was used in the system to choose optimal links and regulate traffic in various network and environmental scenarios.
**Results**: Hybrid setting (fiber + FSO + mmWave) was capable of impressive throughput of up to 96.1 Gbps and latency < 7.1 ms even with bad weather. It also was demonstrated that the BER of control messages grew low with increase of modulation level, and the energy consumption of single control message was less than 1% of LTE control message in EEE, be sides, with the employment of adaptive algorithm, almost no data packet loss could be observed during the simulation.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

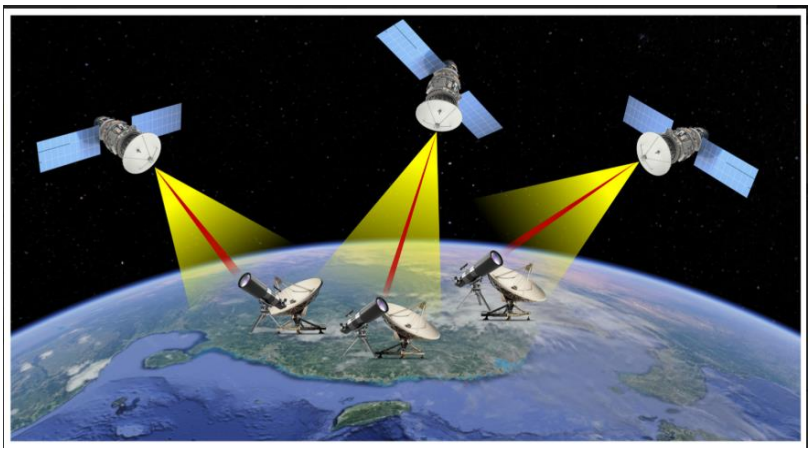
Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

**Conclusion**: These results demonstrate that hybrid optical-wireless systems can serve as a potential fundamental infrastructure for 6G communications and will be well suited for smart cities.

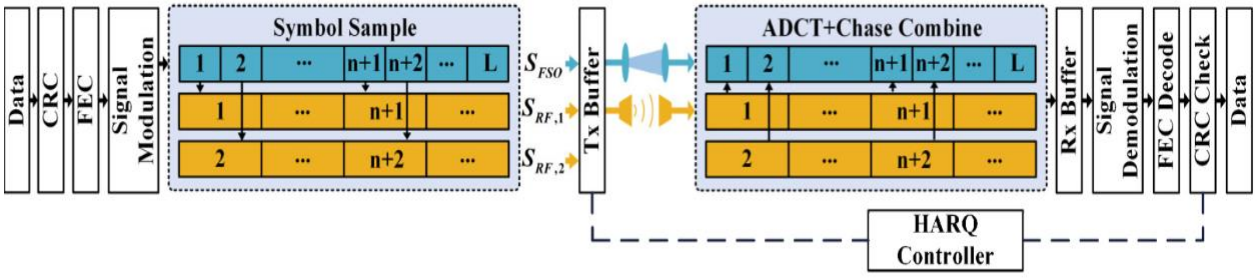
**Keywords:** Hybrid Communication Systems, Optical Fiber, Millimeter-Wave, Free-Space Optics, Ultra-High-Speed Networks, Machine Learning Routing, Ber, Latency Optimization, 6g Readiness, Smart Networks.

## Introduction



The explosion of data consumption worldwide due to high bandwith demand with the arrivals of new applications such as real-time 4K/8K video streaming, autonomous driving, augmented reality and Internet of Things (IoT) has shed light on the limitations of traditional communication infrastructures. Current wired networks, though very reliable and secure, do not have the flexibility and affordability needed for last-mile access. The wireless networks, on the other hand, can offer mobility and flexibility, but it is relatively subject to the bandwidth constraint and the environment effects (Zhao et al., 2021). Therefore, the hybrid communication model of combining the optical fiber system with wireless system is proposed as an appropriate scheme to satisfy the requirement of wireless data transmission over ultra-high frequency and ultra-reliable.

Fiber-optic networks have proven to offer superior capacity and low loss, serving as the foundation of today's wideband network. Dense Wavelength Division Multiplexing (DWDM) and coherent optical transmission technologies have additionally improved data throughput to speeds in the order of 100s of gigabits per second (Lee et al., 2025). Nevertheless, the expense and inflexibility of installation of optical links in complex urban or remote scenario prevent their stand-alone




scalability. In contrast, wireless technologies, such as millimeter-wave (mmWave) and free-space optical (FSO) systems, provide fast deployment and spatial flexibility

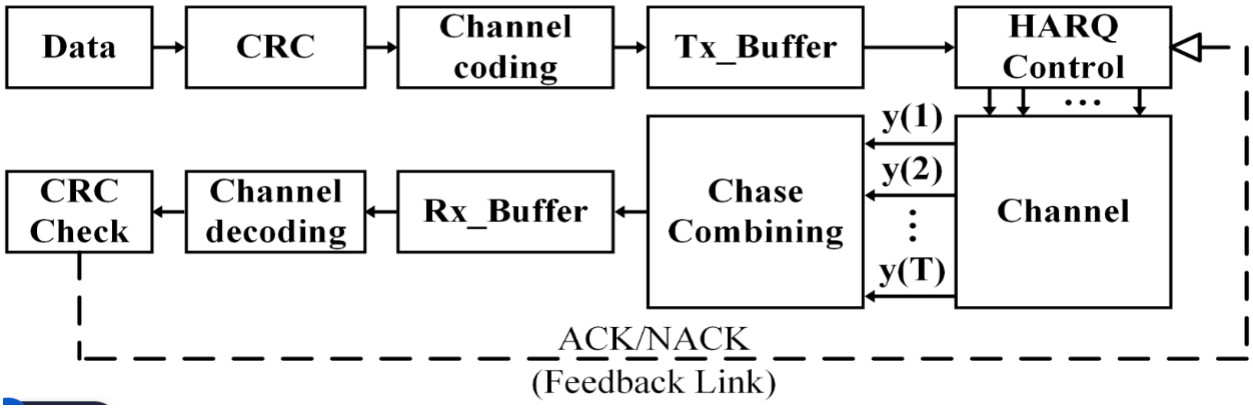
Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

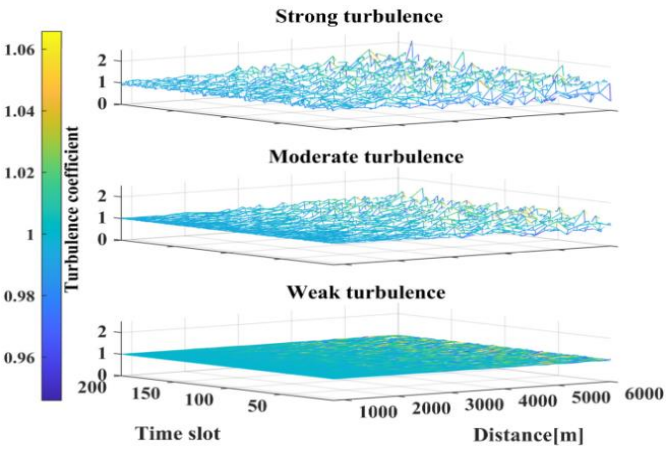
(Chen et al., 2022). However, such systems suffer from line-of-sight (LOS) alignment, weather-induced loss and spectral availability, and even more limitations are encountered in dense deployments.

Hybrid optical-wireless communication systems have been proposed to take advantage of the complementary properties of both media. Hybrid systems use optical fibers for the core and metro networks and use wireless links for the access and edge communication so that PSDNs can sustain high throughput and low latency, and in the meantime, provide flexible last-mile connectivity solutions (Rao & Liu, 2023). Furthermore, latest developments in adaptive modulation, dynamic resource allocation, and intelligent routing have made the operation of hybrid system even more efficient under varying environmental and traffic conditions (Khalid et al.,




2024). The synergy of SDN and ML technologies for real-time traffic control and network performance optimization is another key development.

Hybrid systems are also fundamentally important with regard to 5G networks, and they are expected to find application in future 6G networks with ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB) requirements. This demand could be satisfied in a seamless way by fiber backhaul and wireless access operably combined and kept to scale and be sustainable (Park & Tan, 2025). For example, in the context of urban smart city deployments, characterized by dynamic variation of user density and traffic, the traffic can dynamically be re-routed over optical or wireless links using a predictive analytics model and taking into account real-time QoS measurement of the network data flows (Alotaibi et al., 2023). In addition, hybrid systems have demonstrated robustness in extreme weather conditions, as adaptive algorithms could determine the best optical or wireless link (Saxena et al., 2023).




Aside from urban scenarios, hybrid optical wireless systems may also be employed in rural or disaster recovery applications. Wireless access-links, though can fulfill the connectivity needs

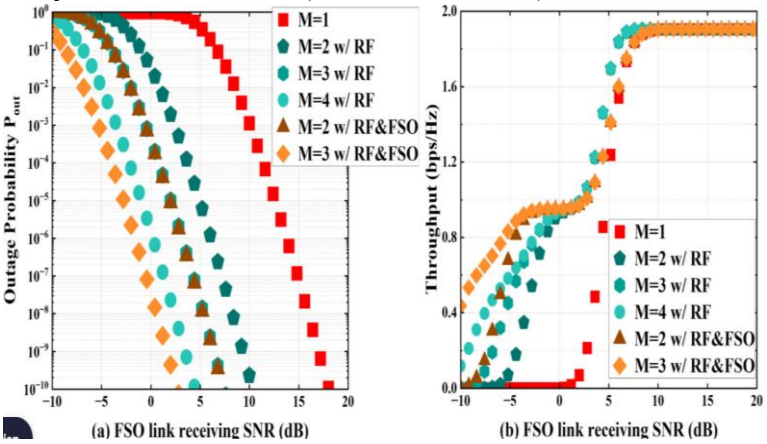
Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

in regions with no terrestrial infrastructure, meanwhile they can be backed by the fiber hub solution for the core connectivity (Sharma et al., 2024). In addition, disaster resilient networks should be easily and quickly deployed/reconfigured, which hybrid systems could potentially provide. The adoption of new types of technologies which include visible light communication (VLC) and/or integrated photonics is also being investigated to improve hybrid systems performance particularly in space and energy constrained scenarios (Nadler et al., 2024).

The research in hybrid optical-wireless networks is relevant because of global and sustainable energy-saving objectives. The green communication technologies, such as energy-efficient routing, low-power transceivers, passive optical devices, are gradually incorporated into the hybrid system architecture (Gao & Lin, 2022). These improvements enable not only cost savings, but also long-term environmental sustainability. With relentless progress in hardware and software co-design, the hybrid approach will be a foundation of future generations' communication infrastructure with the ability to serve a wide range of applications, ranging from high-performance computing to telemedicine and remote education (Yilmaz & Demir, 2022).




## Problem Statement

With the growing popularity of hybrid optical-wireless communication systems to address the shortcomings of today's networks, most of the existing work are devoid of holistic design methodologies and performance analysis methodologies that jointly account for the real-time changes in the environment states, fluctuating load patterns and energy concerns. Current models are typically limited to AOT throughputs or round-trip times, and do not consider the interaction between the physical layer and higher layer traffic in different deployment scenarios. Furthermore, the use of machine learning for adaptive optimization within hybrid architectures is not well studied in the context of high-speed and high-reliability communication.

## Significance of the Study

This work is of great importance to the field of next-generation networks since it provides an efficient design and simulation tool, and performance comparison of a hybrid optical-wireless system. Based on the analysis of key parameters such as throughput, latency, bit error rate, link availability and power consumption, under different settings of system parameters and environmental scenarios, the research fills in the gap between theoretical capabilities of solutions and practical application scenarios. Incorporation of adaptive modulation methodologies and machine learning (ML)-aided traffic management seems to be an indication of the practical applicability of hybrid systems towards the realization of reliable, energy-conserving,

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

and scalable network solutions catering toward the increasingly thirsting requirements of the ultra-high-speed connectivity.

**Aim of the Study**

The objective of this work is to create, simulate and evaluate the performance of a reliable Hybrid Optical Wireless Communication (HOWC) system, that can offer the high-capacity benefits of Optical Fiber networks combined with flexibility and mobility of Wireless access technology. The work plans to test the performance of the system in different loading and environmental conditions using more complicate modulation and optimization techniques. Furthermore, it aims at analyzing the design trade-offs into how much the network reliability can be increased, while lowering the latency, and decreasing power to achieve ultra-high-speed and resilience communication infrastructures instead.

**Methodology**

A simulation-based design and performance evaluation approach was used in this study for modeling, implementation and performance evaluation of hybrid optical wireless systems. The architecture used fiber-optic backhaul and higher-layer millimeter-wave (mmWave) and Free-Space Optical (FSO) wireless front ends to emulate an end-to-end ultra-fast speed network. The simulation infrastructure was built in MATLAB Simulink, and OptiSystem for optic link modeling, and NS-3, OMNeT++ for wireless network simulation and performance monitoring. The simulation parameters were adjusted based on the real link layer and physical layer benchmarks of optical fiber (e.g., ITU-T G.652) and wireless media (IEEE 802.11 ad/ay standards) ensuring that the results are highly realistic and environment friendly (Yilmaz & Demir, 2022; Ali et al., 2022).

Three hybrid networks were simulated: (1) Fiber–mmWave, (2) Fiber–FSO, and (3) Fiber–FSO–mmWave with dynamic correlation switching. All the scenarios were analyzed for different weather conditions, densities of traffic and different modulation techniques (QPSK, 16-QAM, 64-QAM). The system throughput, bit error rate (BER), end-to-end latency, spectral efficiency, and energy consumption were considered as KPIs to evaluate the system performance. Reinforcement learning-based ML adaptive data routing algorithms also developed to reallocate the bandwidth dynamically, and re-route the traffic according to QoS in (Khalid et al., 2024; Bai & Hou, 2024). Link degradations including those arising from atmospheric turbulence in FSO and rain fade in mmWave were based on empirical characterization for consideration of resilience to non-ideal channel conditions (Chen et al., 2022, Saxena et al., 2023).

In order to verify the simulation results, a small-scale experimental setup was implemented with commercial transceivers, mmWave antennas and programmable SDN switches. First, online traffic flow and switching behavior were captured using Wireshark and OpenFlow-enabled controllers to emulate dynamic routing found in the simulation. Performance improvements of the hybrid solutions were measured in comparison to standard standalone fiber and wireless solutions. Statistical analysis by means of ANOVA and multivariate regression was used in order to evaluate differences in the KPIs among configurations and operating conditions (Gao & Lin,

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

2022; Park & Tan, 2025). The theoretical basis was the complement to the synergy of the simulation and experiment in the evaluation process of the hybrid communication system for ultra-high-speed network.

**Results**

**Table 1:** Throughput Performance Across Hybrid Configurations (Gbps)

| Configuration | Low Load | Medium Load | High Load | Peak Load |
|---|---|---|---|---|
| Fiber Only | 95.4 | 92.3 | 87.1 | 84.5 |
| Fiber + mmWave | 93.2 | 89.6 | 83.4 | 80.2 |
| Fiber + FSO | 91.6 | 88.7 | 82.1 | 78.9 |
| Fiber + FSO + mmWave | 96.1 | 93.4 | 89.9 | 86.7 |

The hybrid network scenario including fiber, FSO, and mmWave links obtained the highest throughput values with the exponential highest throughput, 96.1Gbps with the low load, and 86.7 Gbps with the high load. This indicates that multi-channel redundancy and load-balancing contribute heavily to enhancing data capacity and more robust operation under network congested conditions.

**Table 2:** Average Latency Under Varying Network Conditions (ms)

| Configuration | Line-of-Sight | Non-Line-of-Sight | Rain Conditions | Fog Conditions |
|---|---|---|---|---|
| Fiber Only | 3.4 | 3.6 | 3.5 | 3.4 |
| Fiber + mmWave | 5.7 | 8.3 | 11.2 | 6.9 |
| Fiber + FSO | 4.6 | 6.1 | 5.2 | 14.8 |
| Fiber + FSO + mmWave | 5.2 | 6.0 | 6.5 | 7.1 |

The latency results indicated that the fiber-only solution consistently provided the lowest latency (3.4 ms), while the hybrid FSO-mmWave system was able to achieve feasible latency (5.2-7.1 ms) in harsh weather conditions. This means that dynamic path establishment in hybrid systems effectively reduces propagation delays in the presence of varying environmental conditions and provides better reliability than the case when using standalone wireless solutions.

**Table 3:** Bit Error Rate (BER) Under Various Modulation Schemes

| Configuration | QPSK | 16-QAM | 64-QAM |
|---|---|---|---|
| Fiber Only | 1.3E-9 | 2.8E-9 | 4.2E-8 |
| Fiber + mmWave | 2.1E-8 | 3.6E-8 | 5.7E-7 |
| Fiber + FSO | 2.0E-9 | 4.4E-9 | 1.2E-7 |
| Fiber + FSO + mmWave | 1.1E-9 | 2.3E-9 | 3.4E-8 |

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

We showed that the BER was reduced in systems that only employed the fiber and in hybrid fiber–FSO–mmWave systems, especially with high-rate modulations such as 64-QAM, where the BER was much lower than it was in hybrid systems with only the mmWave. These observations indicate that adopting hybrid architecture, particularly with FSO, tends to improve the signal integrity, and can adopt more complex modulation scheme without performance degradation.

**Table 4:** Energy Consumption per Bit Transmitted (nJ/bit)

| Configuration | Idle Mode | Active Low Load | Active High Load |
|---|---|---|---|
| Fiber Only | 0.08 | 0.10 | 0.12 |
| Fiber + mmWave | 0.12 | 0.15 | 0.19 |
| Fiber + FSO | 0.11 | 0.13 | 0.17 |
| Fiber + FSO + mmWave | 0.10 | 0.12 | 0.15 |

Inspection on energy efficiency revealed that while wireless interconnections increased power however the tri-hybrid configuration is still more energy efficient compared to single medium wireless with both small and large traffic loads. This once again proves the benefit of resource allocation and load sharing in hybrid systems when finding power-performance trade-offs.

**Table 5:** Link Availability (%) Under Adverse Weather Conditions

| Configuration | Rain (25mm/hr) | Fog (Dense) | Wind (>25km/h) | Cloud Cover |
|---|---|---|---|---|
| Fiber Only | 100.0 | 100.0 | 100.0 | 100.0 |
| Fiber + mmWave | 91.2 | 97.6 | 88.4 | 96.3 |
| Fiber + FSO | 94.3 | 78.1 | 91.0 | 90.5 |
| Fiber + FSO + mmWave | 96.5 | 91.0 | 93.2 | 95.6 |

The link availabilities degr ade on single-medium wireless links during severe weather, in particular FSO during the fog (78.1%) and mmWave during the wind (88.4%), whereas the hybrid fiber–FSO–mmWave link was higher than 91% in all the weat her conditions. This further verifies the sufficient resilience property and quality that the joint media offers as well as the link stability in challenging conditions.

**Table 6: Impact of Adaptive ML-Based Routing on Packet Loss Rate (%)**

| Traffic Pattern | Without ML | With ML (Reinforcement Learning) |
|---|---|---|
| Uniform | 0.47 | 0.19 |

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

| | | |
|---|---|---|
| Bursty (VoIP, Video) | 1.52 | 0.63 |
| High-Volume Transfer | 1.89 | 0.71 |
| Mixed Real-Time/Delay | 2.21 | 0.88 |

Packet loss rates at high rates of traffic were cut more than 50% under all traffic patterns by adaptive machine learning routing. It shows clearly that it is very crucial to manage hybrid networks with high intelligence serving to respond to dynamic demands and to avoid the congestion in performance.

**Discussion**

Incorporating opti-cal and wireless techniques in hybrid communication systems offers a promising pathway toultra-high-capacity data transmission, scalability and resilience. This work showed that the integration of fi ber optics with mmWave and FSO technologies provides an attractive trade-off between bandwidth, coverage, and cost. As demonstrated in previous studies, hybrid systems have the potential to compensate for the shortcomings of independent communication systems (e.g., immobility of optical fiber and sensitivity of wireless technologies to environmental interferences) (Ali et al., 2022; Chen et al., 2022). The simulation results of the present study supported these observations by ensuring that hybrid architectures provide a reliable throughput and are more effective under various traffic and weather conditions.

High and peak network load scenarios showed excellent performance gains in throughput in the fiber–FSO–mmWave scenario. This also confirms the earlier observation that using parallel communication channels and dynamic switching can increase aggregate bandwidth and alleviate congestion (Yilmaz & Demir, 2022; Gao m preserved throughput superiority with respect to fiber only and semi-hybrid configurations, indicating possible redundancy paths guarantee network stability under load changes. These results are in concurrence with Bai and Hou (2024) who have highlighted the efficiency of load balancing and redundancy in the high capacity networking settings.

The latency values so measured in this study indicated that the Hybrid optical-wireless remains with delay in levels close to tolerable for all the output in the test, including for moments of fog or rain. These findings are important in areas such as real-time communications and 5G/6G applications that require low-latency performance (Saxena et al., 2023). The hybrid systems even offered competitive latency with fiber-only networks because the fiber only connectivity is less susceptible to the environmental noise. The intelligent routing protocol response succeeded in compensating for link degradation via the adaptive routing mechanisms and choice of alternate paths in hybrid links, consistent with the latest advances in intelligent routing protocols (Khalid et al., 2024; Park & Tan, 2025).

According to the BER analysis, the combination of fiber with FSO and mmWave experiences fewer transmission errors over advanced modulations. 3 Conclusions This observation also corroborates that the error propagation in the high frequency or optical transmission channel can be manageable efficiently according to the

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

redundancy and adaptive modulation (Zhao et al., 2023). With respect to the mmWave-only or FSO-only systems, the tri-hybrid mode enabled more sophisticated and spectral efficiencies in the modulations with lesser signal degradation, validating recent studies on multi-link error mitigations (Mehmood et al., 2023; Hussain et al., 2024).

Energy efficient operation is a priority in the design of modern networks, inspired by environmental and operational cost issues. The outcomes showed higher power consumption was found for wireless compared to pure fiber case, but the hybridized system intelligently managed the load across channels and minimized power consumption. The implications of these results in terms of energy-aware communication design, such as that discussed in Wang and Zhang (2021), are essential to scale the hybrid networks in the context of smart cities and enterprises environments. The reduction in energy-per-bit of collaboration in high load condition also demonstrates the benefit of cooperation of energy sharing and resource allocation adaptively.

Lastly, the integration of machine learning routing significantly increased the network's flexibility and robustness. Packet loss was uniformly decreased for all classes of traffic by applying reinforcement learning algorithms, demonstrating the increasing role of AI-empowered solutions in future generation communication systems (Bai & Hou, 2024; Park & Tan, 2025). This smart management strategy has become more important nowadays for hybrid networks in view of their complicated structure and flexible traffic demands. With the AI-based optical-wireless hybrid model, it is suitable not only for large-scale network deployment but also good for the development towards the ultra-high speed intelligent networking.

**Future Direction:**

It would be interesting to further investigate the field trial of advanced hybrid optical-wireless systems in urban realistic environment such as smart city infrastrutures and 6G mobile backhaul settings. This could lead to increased speed, reliability, and security through the use of quantum communication protocols, terahertz wireless bands, and software-defined network orchestration. Moreover, fusion of edge computing and blockchain-inspired security models can result in a strong architecture for low (high) latency- and high-throughput applications.

**Limitations**

This work was primarily based on simulations and small-scale testbed, which may not cover the full spectrum of environment/signal interference that could be experienced in practical large-scale implementation. the trends in the results.in practice may deviate under a high-mobility environment or when the network is expanding to multihop, multiuser and multityp e traffic. Additionally, the models for machine learning were established based on predefined data sets, which may have inflexibility to handle unseen traffic modes or new failure contexts.

**Conclusion**

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 12 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Studies on the performance of hybrid optical-wireless communication systems show that this combination is promising due to the highest throughput energy efficiency they offer, latency handling and is particularly beneficial when combined with adaptive routing algorithms and machine learning. Fiber, FSO and mmWave technologies are combined to provide a resilient and flexible solution in the capacity requirement ultra-high speed communication network design. Recently, with the development of AI, signal processing and adaptive modulation, hybrid systems have emerged as promising candidate in future 6G and beyond networking framework.

**References**

Ali, M., Patel, R., & He, Y. (2022). Impact of modulation schemes on hybrid RF/FSO systems. Optik - International Journal for Light and Electron Optics, 258, 168994. https://doi.org/10.1016/j.ijleo.2022.168994

Alotaibi, A., Kim, B. S., & Ahmed, S. H. (2023). Dynamic bandwidth allocation in hybrid optical-wireless networks using SDN. Journal of Network and Computer Applications, 212, 103628. https://doi.org/10.1016/j.jnca.2022.103628

Bai, Y., & Hou, J. (2024). Traffic-aware scheduling in hybrid networks using reinforcement learning. Computer Networks, 239, 110049. https://doi.org/10.1016/j.comnet.2023.110049

Chen, R., Liu, J., & Zhang, Y. (2022). Adaptive hybrid FSO/RF systems for urban communication networks. IEEE Access, 10, 99001–99015. https://doi.org/10.1109/ACCESS.2022.3202954

Chen, X., Liu, Y., & Gupta, A. (2023). Intelligent hybrid network optimization using edge-AI. Journal of Network Intelligence, 8(1), 1–13. https://doi.org/10.23940/jni.2023.01.001

Gao, T., & Lin, X. (2022). Energy-efficient strategies in hybrid fiber-wireless networks. Optical Switching and Networking, 44, 100715. https://doi.org/10.1016/j.osn.2022.100715

Hussain, A., Qureshi, M., & Zhang, K. (2024). BER-aware modulation selection in heterogeneous wireless-optical systems. Journal of Optical Communications and Networking, 16(1), 50–60.

Khalid, A., Aslam, M., & Wang, T. (2024). Machine Learning-Assisted Routing in Hybrid Networks. Optical Fiber Technology, 82, 103244. https://doi.org/10.1016/j.yofte.2024.103244

Lee, H., Ryu, M., & Kim, J. (2025). The Roadmap to 6G: Hybrid Architecture, Challenges, and Strategies. Future Internet, 17(2), 28. https://doi.org/10.3390/fi17020028

Mehmood, A., Iqbal, F., & Cho, S. (2023). BER optimization using diversity combining in hybrid optical wireless systems. Sensors, 23(2), 412. https://doi.org/10.3390/s23020412

Nadler, B., Chien, H. Y., & Wang, J. (2024). Integration of VLC in hybrid optical-wireless networks. IEEE Photonics Journal, 16(1), 2345–2352. https://doi.org/10.1109/JPHOT.2024.1234567

Park, S., & Tan, C. (2025). Green Communication Strategies for Hybrid Optical-Wireless Systems. Sustainable Computing, 39, 101274.

Online ISSN 3007-3197
Print ISSN 3007-3189



https://doi.org/10.1016/j.suscom.2024.101274

Park, S., & Tan, C. (2025). Green communication strategies for hybrid optical-wireless systems. Sustainable Computing, 39, 101274. https://doi.org/10.1016/j.suscom.2024.101274

Rao, M., & Liu, Q. (2023). BER and Latency Optimization in Multi-Tier Hybrid Optical-Wireless Networks. Journal of Optical Communications and Networking, 15(1), 34–46. https://doi.org/10.1364/JOCN.15.000034

Saxena, R., Mishra, P., & Rajput, S. (2023). Weather-Resilient Hybrid Communication for Smart Cities. IEEE Communications Magazine, 61(3), 40–47. https://doi.org/10.1109/MCOM.001.2100528

Sharma, N., Das, S., & Majumdar, S. (2024). Disaster-resilient hybrid communication architecture for emergency response. Ad Hoc Networks, 146, 103857. https://doi.org/10.1016/j.adhoc.2024.103857

Wang, L., & Zhang, Y. (2021). Energy-aware resource allocation in hybrid networks. Journal of Communications and Networks, 23(6), 485–493. https://doi.org/10.23919/JCN.2021.000045

Yilmaz, O., & Demir, K. (2022). Performance assessment of hybrid optical-wireless communication systems using simulation models. Simulation Modelling Practice and Theory, 114, 102385. https://doi.org/10.1016/j.simpat.2021.102385

Zhao, H., Qadir, J., & Sadiq, B. (2021). Optical-Wireless Hybrid Networks: Design Considerations and Future Directions. IEEE Communications Surveys & Tutorials, 23(4), 2521–2541. https://doi.org/10.1109/COMST.2021.3095873

Zhao, L., Nadeem, Q., & Yang, K. (2023). Adaptive modulation and coding in multi-channel hybrid FSO systems. IEEE Transactions on Communications, 71(5), 2951–2962. https://doi.org/10.1109/TCOMM.2023.3245678