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A Critical Survey of Free Space Optics for 6G Fronthaul Networks

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ABSTRACT

The emerging Sixth-Generation (6G) wireless framework requires network architectures capable of sustaining terabit-per-second (Tbps) peak data rates, ultra-low latencies below 100 µs, and massive ultra-reliable low-latency communications (mULC) that can accommodate huge traffic demands becomes a crucial aspect for enhancing the overall system performance. Free space optics (FSO) is a line of sight technology with promising characteristics like high bandwidth, low latency, unlicensed spectrum, speedy propagation, narrow beam, inherent security and high flexibility with the possibility of surpassing certain radio technologies. The FSO technology offers best of the both, being optical in nature and wireless in transmission and reception. The present work provides a comprehensive review of using FSO as a feasible solution for 6G front haul networks because of its numerous advantages. In this paper, we have reviewed the major features of FSO, while also identifying critical barriers such as atmospheric attenuation, alignment sensitivity and mobility constraints during its implementation in 6G networks.

Keywords: Free Space Optics (FSO), 6G Fronthaul, Ultra-reliable low-latency communications (mULC), Terabit-per-second (Tbps), Hybrid FSO/RF, Reconfigurable Intelligent Surface (RIS).

INTRODUCTION

The sixth generation (6G) of mobile communications is on the horizon and we are moving toward the "connected world" where "everything" will be connected to the network. The sixth generation (6G) of wireless networks is envisioned to exceed the capabilities of 5G by offering data at the rate of terabits-per-second and low latency connection under 100 microsecond (μs), significantly surpassing the previous generations [2].

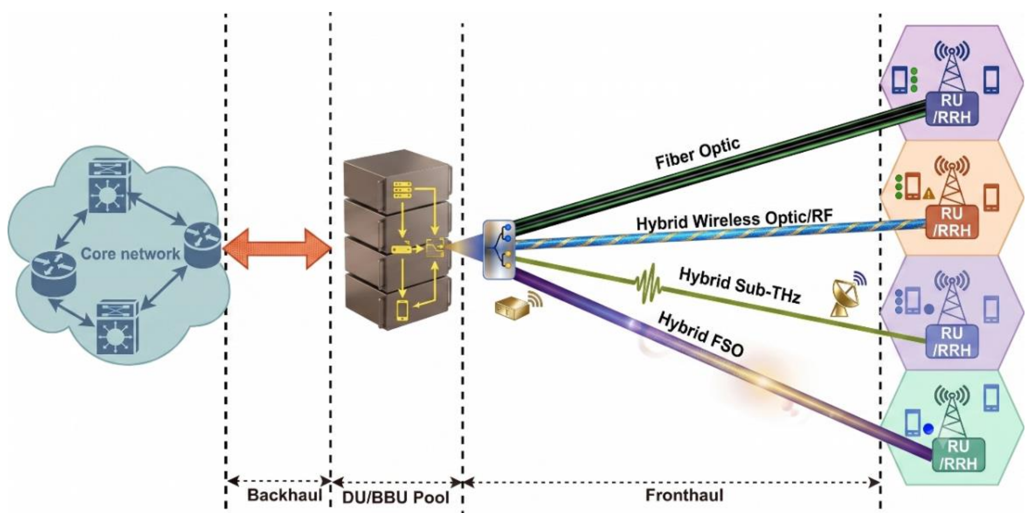

Fig. 1. Centralized network architecture

For better network characteristics and to meet the increasing demand for high capacity and low latency, the front haul plays an essential role as illustrated in Figure 1. The efficiency with which communication occurs is highly dependent on the front haul part. It acts as a linkage between the remote units (RUs) or remote radio heads (RRHs) and the central digital unit (DU) or baseband unit (BBU). On the other hand, the backhaul connects the DU/BBU pool to the core network [3-5].

The *ultra-reliable low-latency broadband communications (ULBC)* use-case enhances reliability and low-latency communications with ultra-fast connection, enabling even more critical applications and services.
Building upon the ultra-reliable low-latency communications (URLLC) use-case of the fifth generation (5G) of mobile communications, *Massive Ultra-reliable Low-latency Communications* (mULC) will deliver even higher reliability and lower latency, with focused mission-critical applications requiring high precision and responsiveness. This has its use in autonomous transportation, remote surgery and advanced robotics industries.
Further, we can improve the mobile broadband capabilities to offer seamless connection and transmission at high-speed at any location using *Ubiquitous Mobile BroadBand* (uMBB). It will enable pervasive access to the Internet, allowing users to enjoy multimedia experiences and stay connected at any location.

Fronthauling

(i) Design of Fronthaul Part

As the entire network efficiency is dependent on the front haul part, it becomes necessary to determine which technology should be used in Fronthaul so that efficiency can be increased. The concept of Fronthauling in future 6G can be challenging due to numerous reasons:

- As the upcoming generation 6G is advancing to 100 times faster than 5G, the design of Fronthaul network must offer high-capacity connections which is a challenging task to design.
- When we increase the number of antennas and RUs, it leads to significant increase in the complexity of the front haul network, thereby difficult to deploy, manage and maintain.
- 6G supports ultra-low latency real-time applications. This brings forth the need for real-time data processing and transfer, a challenging task for the front haul network.
- Due to integrated technology and increased complexity, Security can be complicated. To satisfy such requirements, the design must ensure security against potential cyber threats and data privacy should be maintained.
- The deployment of optical fiber would be very expensive for large-scale deployment scenarios of RU’s.

Types of Fronthaul Solutions

With advancement in communication technology, the traditional methods of front haul solutions like copper, RF communication and optical fiber cables fail to achieve the evolving demands of 6G networks.
The front haul technologies are compared on the basis of several parameters as shown in Table 1.

Table 1: Comparison of different technologies

Factors	Technologies					
	RF link	Sub-GHz wave	Mm wave	Sub-THz wave	Fiber Optic Cable	FSO
Range	Long	Long	Short (up to few km)	Short (up to few km)	Long	Short (up to few km)
Licensing	Requires licensing	Requires licensing	Requires licensing	Requires licensing	Requires licensing	License-free
Speed of deployment	Moderate	Moderate	Moderate	Moderate	Slow	Rapid
Data Rate	10 Mbps to several Gbps	Up to 100 Mbps	Up to 10Gbps	Up to 100 Gbps	Up to 100 Gbps and beyond	Up to 100 Gbps
Cost	Moderate	Low/moderate	Moderate	High	High	Moderate
Reliable	Moderate	High	Moderate	Moderate	High	Moderate

The FSO technology has gained interest due to its widespread advantages and has engrossed the researchers to work towards development of FSO communication system for extended reach with high data rate applications. It provides lower latency and higher bandwidth compared to certain radio technologies [6]. It is also faster than optical fiber cables because the light travels faster through air than it does through glass. It even retains moderate deployment costs and rapid deployment time frames while also uniquely being license-free [7].

Notwithstanding its many encouraging attributes, FSO has many issues that require attention. The strict LOS requirements for FSO lines are one major obstacle. Rain, snow, dust storms, fog, and other meteorological conditions can also be harmful because they weaken or scatter optical signals. This, of course, calls into question the performance and dependability of FSO links.

The robustness and overall performance of FSO systems can be improved by successfully reducing the effects of unfavorable weather conditions through the development of multiple mitigation strategies.

RELATED WORKS

This section presents a state of art literature survey that covers various key aspects of FSO and Fronthauling based on FSO. Recent studies have extensively examined the performance of Free-Space Optical (FSO) communication systems under various conditions and configurations. The research spans several areas, including modulation techniques, diversity methods, coding schemes and the influence of atmospheric factors on the performance of FSO Communication link [8-10].

The authors in [11] have described the advantage of Optical wireless communication (OWC) over RF communication due to frequency allocation issue and the recent advances and future perspectives in OWC, free-space-optical (FSO) communication and sensing, from devices to applications.

In the survey by Jahid et al. [12], the authors examine the possible uses, difficulties, fixes and future directions of FSO systems while contrasting them with other optical wireless technologies. In the context of 5G and beyond, the Internet of things/Internet of everything (IoT/IoE), and space communications, they also emphasize the latest developments and emerging trends of FSO systems.

The authors of a further study [13] suggest a unique way to handle traffic demands by combining retro modulator-based FSO communication with unmanned aerial vehicle (UAV) technologies. The article presents a novel radio access network architecture driven by edge computing, in which FSO is employed for front haul and backhaul links installed on unmanned aerial vehicles.

Aboelala et al. explore the applicability of FSO for for improving backhauling in 5G and beyond networks [14]. They point out FSO's drawbacks, especially how susceptible it is to interference and bad weather. They examine methods to maximize data rate and bit error rate (BER) in 5G networks and survey current hybrid FSO/RF systems in order to overcome these problems.

In [15], the authors have designed an FSO communication system model with remodeled refractive index structure profile parameter that can be exploited in mountainous locations or in difficult terrains with abundant rainfall where other technologies can’t be deployed due to limiting features. The validation has been done by simulating a designed FSO system between two hills of Arunachal Pradesh (North Eastern State of India) by using Meteorological (MET) data. According to the analysis, in order to accurately calculate path losses and construct a dependable and failsafe FSO communication system, the modified model should be employed in place of standard models.

Coding strategies are essential for minimizing BER, particularly in challenging transmission environments. The authors in [16] explored four channel coding techniques, revealing that Turbo Codes (TC) and convolution codes significantly improved performance under moderate to strong turbulence conditions. Similarly, [17] evaluated a concatenated coding scheme in an OFDM-based FSO system, demonstrating superior performance over individual coding approaches.

The analysis of coding techniques continued with [18] and [19], which examined the performance of TC in the presence of various channel impairments, such as AWGN and fading. Both studies highlighted the criticality of selecting appropriate coding schemes to maintain acceptable BER levels across different fading conditions.

In [20], the authors have investigated the error performance of the designed FSO communication system using RS codes in turbulent conditions at higher data rates under several nonlinearities using Modified model. The designed FSO system with forward error correction coding (FEC) worked optimally in comparison to the conventional FSO system, with geometric losses reduced due to increase in error correction capabilities.

A further research article [21] shows that the FSO-based vertical backhaul/front haul frame- work can provide higher data rates than other alternatives, making it a promising solution to the emerging backhaul/front haul requirements of 5G and beyond networks, mainly in the scenarios of ultra-dense heterogeneous small cells.

A comprehensive review of FSO systems in the context of the beyond 5G/6G era is presented by another article [22]. Its authors discuss various aspects such as transceiver design, system architectures, and integration with mmWave/Terahertz (THz) links. Additionally, they explore the potential utilization of machine learning (ML) algorithms in FSO systems.

The mentioned works focus on the applicability of FSO in wireless networks and several techniques that can enhance its performance. A critical comparison of this existing literature is given in table 2:

Table 2: Critical Comparison of Existing Literature on FSO Communication for 6G Fronthaul

Ref No.	Contribution	Technique	Strengths	Limitations	Research Gap Pertinent to 6G Fronthaul
[11]	OWC, FSO and optical sensing overview for 6G	Survey	Discusses recent advances, optical devices, sensing technologies and future 6G applications	Does not investigate practical deployment challenges, latency analysis, or fronthaul architecture	No detailed analysis of AI-enabled FSO fronthaul, beam tracking delay, or system-level performance evaluation
[12]	Comprehensive survey on FSO communication, challenges, mitigation techniques and applications	Survey	Reviews FSO technologies, IoT, IoE, space communication, and hybrid systems	Primarily focuses on FSO communication in general rather than dedicated 6G fronthaul deployment	Lacks architectural integration, mathematical modeling, and ultra-low latency analysis for 6G
[13]	Edge-computing enabled UAV-mounted FSO fronthaul and backhaul architecture	System architecture	Introduces UAV-assisted FSO with edge computing for flexible deployment	Limited to UAV scenarios and 5G architecture; does not consider AI-native 6G requirements	No discussion on synchronization, AI-based beam control, or ultra-dense 6G fronthaul networks
[14]	Survey of hybrid RF–FSO communication for 5G backhaul	Survey	Discusses hybrid RF/FSO systems and BER optimization under adverse weather	Primarily addresses backhaul rather than fronthaul and focuses on 5G networks	Does not investigate AI-assisted hybrid switching or 6G latency constraints
[15]	Modified atmospheric turbulence model incorporating rainfall for FSO links	Mathematical modelling and simulation	Improved path loss estimation under mountainous terrain using MET data	Application restricted to channel modelling and specific geographical conditions	Does not evaluate complete 6G fronthaul architecture or network-level performance
[16]	Investigation of channel coding and time diversity techniques	Simulation	Demonstrates BER improvement using Turbo and	Considers only physical layer coding	No consideration of latency, fronthaul

			convolution codes	performance	architecture, or AI-enabled communication
[17]	Hybrid channel coding for OFDM-based FSO communication	Simulation	Improves BER under weak atmospheric turbulence	Focuses only on coding performance	Does not address network architecture, beam alignment, or 6G deployment
[18]	BER analysis of Turbo-coded OFDM system	Simulation	Evaluates BER performance under noisy channels	Limited to AWGN channel analysis	Does not consider atmospheric turbulence, beam tracking, or fronthaul applications
[19]	Performance evaluation of Turbo coding under different noise conditions	Simulation	Demonstrates coding gain under multiple noise environments	Restricted to coding performance	No investigation of real-world FSO deployment challenges or 6G requirements
[20]	Reed–Solomon forward error correction for FSO communication	Simulation	Significant BER improvement under atmospheric turbulence	Focuses only on physical layer error correction	Does not study AI-based optimization, fronthaul architecture, or latency-sensitive applications
[21]	Vertical FSO backhaul/fronthaul framework for 5G+ networks	Network architecture	Demonstrates suitability of FSO for ultra-dense heterogeneous networks	Primarily targets 5G+ and does not investigate AI-native networking	Limited discussion on synchronization, adaptive beam steering, and intelligent resource management
[22]	Review of FSO communication systems for B5G/6G	Review	Covers transceiver design, system architecture, THz integration, and machine learning	High-level overview without quantitative analysis or deployment framework	No mathematical modelling, simulation framework, or AI-native 6G fronthaul architecture

This indicates that a significant research has been conducted on FSO from different perspectives, including optical channel modeling, hybrid RF–FSO communication, coding techniques, UAV-assisted deployment and optical wireless communication surveys. Though these studies provide a better understanding of FSO communication but they focus more on improving physical-layer performance, atmospheric channel modeling, or 5G-oriented backhaul and fronthaul applications.

However, less attention is given to harnessing it for future 6G Fronthaul. Followed by these research gaps, the present work investigates FSO as a potential fronthaul solution for AI-native 6G networks by:

(i) evaluating the performance of FSO Link under atmospheric effects through simulation
(ii) discussing ultra-low latency and synchronization challenges unique to 6G
(iii) Identifying future research directions involving Digital Twins, Hybrid THz–FSO communication, RIS-assisted optical links and federated learning for intelligent fronthaul management.

FUTURE RESEARCH DIRECTIONS

Although significant progress has been made in FSO communication, several technical challenges remain before it can become a reliable front haul solution for future AI-native 6G networks. Emerging technologies such as artificial intelligence (AI), digital twins, intelligent surfaces, quantum communication and integrated terrestrial-satellite architectures present promising opportunities to improve the performance, reliability and scalability of FSO systems. The following research directions are expected to play a crucial role in realizing next-generation FSO-enabled 6G front haul networks:

CONCLUSION

FSO has emerged as a promising fronthaul technology for 5G and future 6G networks due to its ability to provide ultra-high data rates, low latency, large bandwidth and rapid deployment. Despite these advantages, its performance is still affected by atmospheric attenuation, beam misalignment and weather conditions. The mathematical modeling and simulation results presented in this study confirm that atmospheric attenuation and pointing errors remain the primary factors limiting FSO performance. Among different weather conditions, heavy fog causes the most significant signal degradation, while clear atmospheric conditions can maintain satisfactory signal quality over a 2 km communication link.

The study also highlights that integrating AI-assisted adaptive beam tracking and hybrid RF–FSO architectures can substantially improve link reliability, reduce communication interruptions, and satisfy the stringent latency requirements of future 6G fronthaul networks. Furthermore, emerging technologies such as Artificial Intelligence, Digital Twins, Reconfigurable Intelligent Surfaces, Quantum Communication, Cell-Free Massive MIMO, LEO satellite integration and FL have the potential to transform FSO into an intelligent, autonomous and highly secure communication platform.

Overall, FSO is expected to become a key enabler of next-generation wireless networks. Continued research on intelligent optimization, robust hybrid architectures and advanced security techniques will accelerate its practical deployment, paving the way for reliable, high-capacity and future-ready 6G communication systems.

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