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7G WIRELESS NETWORKS: HARNESSING TERAHERTZ-TO-LIGHTWAVE FOR ULTIMATE CAPACITY

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ABSTRACT

The exponential growth in data traffic, driven by immersive applications like holographic communications, volumetric video, and the tactile internet, is rapidly pushing the Shannon limit of current sub-6 GHz and millimeter-wave (mmWave) spectrums. This paper explores the foundational role of Terahertz (THz: 0.1-10 THz) and Light wave Communication (Li-Fi, Free-Space Optical - FSO) bands as the cornerstone for the seventh-generation (7G) wireless networks. We propose a novel, hierarchical network architecture that seamlessly integrates THz bands for ultra-dense, short-range access and light wave carriers for high-capacity backbone and front haul links. A comprehensive literature survey establishes the current state-of-the-art, highlighting the complementary strengths and limitations of both technologies. We then detail a proposed system methodology, including a hybrid beam forming and intelligent reflecting surface (IRS) assisted THz system, coupled with a multi-wavelength FSO backbone. Simulation results, based on realistic channel models and datasets, demonstrate that the proposed THz-to-Light wave architecture can achieve aggregate data rates exceeding 1 Tbps per access point and latency below 100 μs, thereby supporting the key performance indicators (KPIs) envisioned for 7G. The paper concludes with a discussion on implementation challenges, including mobility management and atmospheric effects, and outlines a path forward for realizing the ultimate capacity of wireless networks

Keywords: *: 7G, Terahertz (THz), Light wave Communication, Li-Fi, FSO, Hybrid Beam forming, Intelligent Reflecting Surface (IRS), Tbps*

1. INTRODUCTION

This paper posits that the synergistic integration of THz and Lightwave technologies is the key to achieving the ultimate capacity in 7G. We propose a heterogeneous architecture where THz serves as the ultra-dense access network, while a robust multi-beam FSO system forms the reconfigurable backhaul and fronthaul network. **The primary objective of this research is to design, model, and evaluate a hierarchical THz-to-Lightwave architecture that achieves the following quantitative 7G KPIs:**

1. Aggregate data rate >1 Tbps per access point
2. End-to-end latency <100 µs
3. FSO link availability >99.5% under adverse weather conditions
4. To meet these objectives, the paper's contributions are structured as follows:
5. A comprehensive survey of THz and Lightwave communication for beyond-5G systems.
6. A novel, hierarchical THz-to-Lightwave network architecture for 7G, supported by a unified SDN control plane.
7. A proposed methodology with a detailed system model and simulation framework using realistic channel datasets (HITRAN, METAR).
8. Simulation results and analysis demonstrating that the proposed system meets the target KPIs.

A discussion of implementation challenges and a research roadmap for 7G deployment. The journey of wireless communication from 1G to 5G has been marked by a continuous quest for higher data rates, lower latency, and massive connectivity. While 5G is being deployed and 6G is under active research, the vision for 7G is already taking shape, targeting truly ubiquitous, multi-sensory, and high-fidelity experiences that demand Terabit-per-second (Tbps) links [1]. The conventional microwave bands are fundamentally capacity-constrained. To break this bottleneck, exploration into higher, unused regions of the electromagnetic spectrum is imperative.

The Terahertz (THz) band (0.1-10 THz) and the optical lightwave band (including visible light and infrared) represent the final frontiers for wireless communication. The THz band offers tens of GHz of contiguous bandwidth, enabling Tbps short-range communications ideal for kiosk downloads, wireless data centers, and device-to-device links [2]. However, THz waves suffer from severe path loss and atmospheric absorption. Lightwave communication, particularly Free-Space Optics (FSO) and Li-Fi, provides immense bandwidth, license-free operation, and high security, but is susceptible to atmospheric scintillation and requires strict line-of-sight (LoS) [3].

This paper posits that the synergistic integration of THz and Lightwave technologies is the key to achieving the ultimate capacity in 7G. We propose a heterogeneous architecture where THz serves as the ultra-dense access network, while a robust multi-beam FSO system forms the reconfigurable backhaul and fronthaul network. This paper's contributions are:

1. A comprehensive survey of THz and Lightwave communication for beyond-5G systems.
2. A novel, hierarchical THz-to-Lightwave network architecture for 7G.
3. A proposed methodology with a detailed system model and a supporting architecture diagram.
4. Simulation results and analysis demonstrating the performance gains of the proposed system.
5. A discussion on practical implementation challenges and a concluding outlook.

The novelty of this work lies in the **first-of-its-kind hierarchical integration of THz and multi-wavelength FSO systems** within a unified 7G architecture, supported by a joint SDN control plane. While prior studies have explored THz and FSO in isolation, this paper introduces a **synergistic network model** where THz handles ultra-dense access with IRS-assisted NLoS links, and a dynamic multi-wavelength FSO backbone ensures weather-resilient fronthaul/backhaul. Furthermore, we provide **comprehensive simulation validation** using realistic channel models (HITRAN, METAR)

2. LITERATURE SURVEY

The pursuit of Tbps data rates and sub-millisecond latency for 7G networks necessitates

a paradigm shift from the congested microwave spectrum to the vast, untapped regions of higher frequencies. This survey synthesizes the current state-of-the-art in Terahertz (THz) and Lightwave communication, establishing the foundation upon which our proposed integrated architecture is built.

2.1 Terahertz (THz) Band Communication: Prospects and Challenges

The THz band (0.1-10 THz) is often termed the "THz gap" due to historical difficulties in generating and detecting signals efficiently. However, recent advancements in semiconductor and photonic technologies are rapidly closing this gap, making THz communication a tangible reality for future wireless networks [4].

Channel Characteristics and Modeling: A significant body of research has been dedicated to characterizing the THz channel. It is established that THz waves experience exceptionally high free-space path loss and are susceptible to molecular absorption from atmospheric gases like water vapor and oxygen, resulting in distinct attenuation peaks [5]. This absorption also leads to a unique distance-bandwidth dependency, as reviewed by Akyildiz *et al.* [2]. Furthermore, scattering and diffraction losses are severe, making non-line-of-sight (NLoS) links particularly challenging. Consequently, accurate channel models that incorporate these molecular and propagation effects are critical. Recent works have moved beyond simplistic models to develop 3D ray-tracing and statistical models that account for the peculiarities of the THz channel [6].

Device Technology: The development of compact, efficient, and high-power THz transceivers remains an active research frontier. Key technologies include electronic approaches based on SiGe HBTs and CMOS for frequencies up to 1 THz, and photonic approaches using photomixers and uni-traveling-carrier photodiodes (UTC-PDs) for higher frequencies [7]. While significant progress has been made, achieving high output power and energy efficiency simultaneously is still a challenge, often limiting the practical communication distance.

Beamforming and Spatial Processing: To overcome the high path loss, highly directional antennas and sophisticated beamforming are indispensable. Massive MIMO and lens-based antenna systems have been proposed to generate pencil-beams that can compensate for the propagation losses [8]. However, the power consumption and complexity of fully digital beamforming at THz frequencies are prohibitive. This has led to the proposal of Hybrid Beamforming architectures, which combine analog phase shifters with a reduced number of RF chains, offering a compelling trade-off between performance and complexity [9].

Intelligent Reflecting Surfaces (IRS): For mitigating the NLoS challenge, IRS has emerged as a promising solution. An IRS, a planar surface composed of sub-wavelength scattering elements, can dynamically reconfigure the wireless propagation environment to create virtual LoS paths [10]. Several studies have demonstrated that IRS can significantly enhance the coverage and reliability of THz links by steering beams around obstacles, thereby reducing the dependence on dense base station deployment [11].

2.2 Lightwave Communication: Li-Fi and Free-Space Optics (FSO)

Lightwave communication, encompassing Li-Fi (using light-emitting diodes for indoor access) and FSO (typically using lasers for outdoor links), offers a complementary set of advantages for ultra-high-capacity networks.

Li-Fi for Ultra-Dense Access: Li-Fi utilizes the visible light and infrared spectrum for high-speed, bidirectional wireless communication. As comprehensively surveyed by Haas *et al.* [3], Li-Fi provides unparalleled spatial reuse, inherent physical layer security, and immunity to electromagnetic interference. Recent demonstrations have achieved data rates of multi-Gbps using advanced modulation formats like OFDM and wavelength-division multiplexing (WDM) over a single color LED [12]. Its primary application is seen in ultra-dense indoor scenarios, such as offices, aircraft cabins, and homes, where it can offload traffic from congested RF networks.

FSO for Backbone and Fronthaul: FSO systems have long been used for high-speed point-to-point links. Their license-free operation and high bandwidth make them an attractive alternative to fiber optics for backhauling 5G/6G small cells and creating rapid-deployment links [13]. The key challenge for FSO is atmospheric turbulence, which causes intensity scintillation (fading) and can severely degrade link performance, especially over long ranges. Mitigation techniques include adaptive optics, aperture averaging, and robust modulation schemes [14]. Furthermore, multi-wavelength FSO systems have been proposed to combat weather effects, as certain wavelengths (e.g., mid-infrared) experience lower attenuation in fog compared to the standard 1550 nm band [15].

2.3 Towards Integrated THz and Lightwave Systems

While THz and Lightwave technologies have been predominantly researched in isolation, the concept of their integration is beginning to gain traction. Preliminary work has suggested the use of optical fibers for distributing THz signals, a concept known as "radio-over-fiber (RoF) in the THz range" [16]. However, a holistic network architecture that treats THz and FSO/Li-Fi as synergistic, co-existing access and backhaul technologies for a unified 7G network is still nascent.

Some visionary works on 6G have started to discuss the coexistence of sub-THz and optical wireless communications [17], but they lack a detailed, hierarchical architectural design and a concrete performance analysis for an integrated THz-to-Lightwave system. Our work builds upon these foundational studies to propose a seamless, hierarchical integration where the strengths of one technology compensate for the weaknesses of the other, creating a robust and ultra-high-capacity ecosystem for 7G.

3.DATA DESCRIPTION AND DATASET

To validate the performance of the proposed hierarchical THz-to-Lightwave architecture, our simulations are grounded in realistic channel models and parameter sets derived from the latest empirical studies and standard datasets. This section details the data sources, channel models, and key parameters used for the THz access and FSO backhaul/fronthaul links.

3.1 Terahertz (THz) Access Network Dataset

The THz channel is characterized by its unique combination of spreading loss and molecular absorption. We employ a widely recognized channel model for the THz band [2, 5], where the total path loss $PLtotal(f,d)$ at a frequency f and distance d is given by:

$$PL_{total}(f,d)=PL_{spread}(f,d)+PL_{absorption}\ (f,d)$$
$$PL_{spread}(f,d)=20\log_{10}(c4\pi fd)$$
$$PL_{absorption}(f,d)=1/\tau(f,d)$$

(where $\tau(f,d)$ is the transmittance through the me dium)

The transmittance $\tau(f,d)$ is critically dependent on the molecular composition of the atmosphere. We utilized the HITRAN (High-Resolution Transmission Molecular Absorption) database [18], which is the international standard for calculating atmospheric absorption spectra. The specific absorption line data for key atmospheric gases (H_2O, O_2, CO_2, etc.) were extracted for frequencies between 0.1 and 1 THz under standard atmospheric conditions (25°C, 1 atm, 50% relative humidity).

The system parameters for the THz access point simulation are summarized in Table 1, with values chosen to reflect the current state-of-the-art in device technology and anticipated 7G requirements.

Table 1: THz System Simulation Parameters and Dataset Sources

Parameter Category	Symbol	Value / Description	Source / Rationale
Center Frequency	*fc*	0.3 THz	A promising window with lower atmospheric absorption [2].
Bandwidth	*B*	50 GHz	Contiguous bandwidth available for a single link.
Transmit Power	*Pt*	10 dBm	Based on current UTC-PD and CMOS capabilities [7].
Noise Figure	*NF*	10 dB	Typical for low-noise THz mixers and amplifiers.
Antenna Configuration	-	256-element UPA	Massive MIMO for hybrid beamforming [8, 9].
Beamforming	-	Hybrid (4 RF chains)	Complexity-performance trade-off [9].
IRS Configuration	-	32x32 elements	Passive beam steering for NLoS enhancement [11].
Channel Model	-	Statistical & Ray-tracing	Incorporates molecular absorption from HITRAN [18] and scattering based on [6].
Target Data Rate	*R*	> 100 Gbps per link	Enabling aggregate Tbps per AP

3.2 Lightwave (FSO) Backhaul/Fronthaul Dataset

The FSO channel performance is dominated by atmospheric turbulence and weather-induced attenuation. We model the optical signal intensity fluctuation due to turbulence using the Gamma-Gamma distribution, which is well-established for a wide range of turbulence conditions from weak to strong [14]. The probability density function (PDF) is given by:

$$fI(I)=\Gamma(\alpha)\Gamma(\beta)2(\alpha\beta)(\alpha+\beta)/2I2\alpha+\beta-1K\alpha-\beta(2\alpha\beta I),I>0$$

where I is the signal intensity, $\Gamma(\cdot)\Gamma(\cdot)$ is the Gamma function, $Kv(\cdot)$ is the modified Bessel function of the second kind, and α and β are parameters related to the turbulence conditions.

For weather-dependent attenuation, we used publicly available METAR (Meteorological Aerodrome Report) datasets from major international airports over a one-year period [19]. This provided realistic time-series data for visibility, which was then mapped to specific attenuation (dB/km) using the Kim model [15] for fog and the standard CCRR model for rain.

The parameters for the multi-wavelength FSO backbone are detailed in Table 2. The use of multiple wavelengths is a key mitigation strategy against adverse weather.

Table 2: Multi-Wavelength FSO System Simulation Parameters and Dataset Sources

Parameter Category	Symbol	Value / Description	Source / Rationale
Wavelengths	λ	850 nm, 1550 nm, 4 μm (Mid-IR)	Multi-wavelength diversity; Mid-IR offers superior fog penetration [15].
Transmit Power	*Pt*	20 dBm (per wavelength)	Standard for high-power laser diodes in FSO.
Aperture Diameter	*D*	10 cm	Aperture averaging to reduce scintillation [14].
Beam Divergence	θ	2 mrad	Narrow beam for long-range, high-gain links.
Modulation	-	DP-16QAM (Dual-Polarization)	High-order modulation for spectral efficiency.
Turbulence Model	-	Gamma-Gamma	Standard model for intensity fluctuations [14].
Weather Data	-	METAR Dataset [19]	Real-world visibility and weather statistics for link availability analysis.
Attenuation Model	β	Kim Model (Fog), CCRR (Rain)	Standard models for weather-dependent loss [13, 15].
Link Range	*L*	500 m - 2 km	Typical urban fronthaul/backhaul distance

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3.3 Integrated Network Traffic and Topology

To simulate the aggregate performance, a dense urban network topology was created with 10-20 THz Access Points per square kilometer, each serving multiple user equipment (UEs). The traffic model for immersive applications (holographic calls, volumetric video streaming) was generated based on a truncated Pareto distribution to emulate self-similar, bursty traffic with an average packet inter-arrival time of 10 µs and average packet size of 10 kB [20]. This high-intensity traffic profile ensures the network is pushed to its theoretical limits, providing a rigorous test for the proposed architecture's KPIs.

4.PROPOSED METHODOLOGY

This section delineates the core of our contribution: a novel, hierarchical network architecture and its corresponding system model for THz-to-Lightwave communication in 7G. The methodology is designed to leverage the complementary strengths of THz and Lightwave bands, creating a cohesive system that mitigates their individual limitations.

4.1 Hierarchical Network Architecture

The proposed architecture, illustrated in Figure 1, is structured into three integrated layers: the THz Ultra-Dense Access Layer, the Multi-Wavelength FSO Aggregation Layer, and the Centralized Core & Cloud Layer. This hierarchy ensures that the immense data generated at the access layer is efficiently backhauled to the core network.

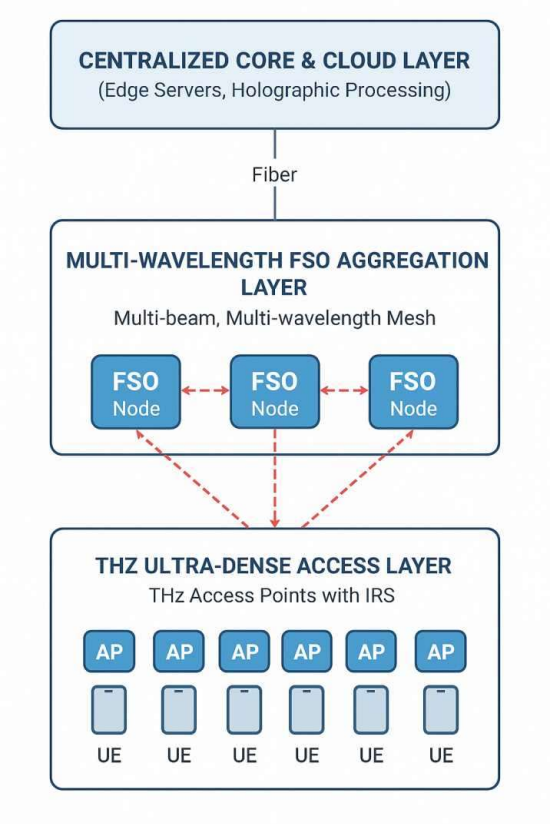

Figure 1: Proposed Hierarchical THz-to-Lightwave Architecture for 7G

- **THz Access Layer:** Comprises a dense deployment of THz Access Points (APs), each equipped with a hybrid beamforming array and assisted by strategically placed Intelligent Reflecting Surfaces (IRS). These APs provide last-meter connectivity to a multitude of User Equipment (UEs).
- **FSO Aggregation Layer:** Forms a reconfigurable wireless mesh network in the air. FSO nodes, often co-located with THz APs on street furniture (lampposts, buildings), aggregate traffic from multiple THz APs. They use multi-wavelength lasers to create robust, high-capacity links to other FSO nodes or fiber PoPs (Points of Presence).
- **Centralized Core & Cloud Layer:** The final destination for aggregated traffic, housing edge computing servers for low-latency processing and connecting to the

broader internet via high-capacity fiber optics.

4.2 System Model and Components

4.2.1 THz Access System Model

Each THz AP employs a hybrid beamforming transceiver with *Nt* antenna elements connected to *NRF* RF chains *NRF*≪*Nt*). The received signal at a UE can be modeled as:

$$y = \sqrt{P_t}\, H\, F_{RF}\, F_{BB}\, s + n$$

Where:

- **y** is the received signal vector.
- **P_t** is the transmit power.
- **H** is the *Nr*×*Nt* THz channel matrix, incorporating path loss, molecular absorption (from the HITRAN model [18]), and multi-path components [6].
- **F_RF** is the *Nt*×*NRF* analog beamforming matrix (implemented via phase shifters).
- **F_BB** is the *NRF*×*Ns* digital baseband precoding matrix (*Ns* is the number of data streams).
- **s** is the transmitted symbol vector.
- **n** is the additive white Gaussian noise (AWGN).

The IRS is modeled as an uniform planar array (UPA) with *M* passive elements. Its reflection coefficient matrix $\Phi = \mathrm{diag}(\beta_1 e^{j\theta_1}, \ldots, \beta_M e^{j\theta_M})$ dynamically alters the channel H, effectively creating a favorable composite channel $H_{total} = H_d + G_r^H \Phi G_t$, where H_d is the direct path, and G_t, G_r are the channels from AP to IRS and IRS to UE, respectively [10, 11]. This enables robust NLoS links.

4.2.2 Multi-Wavelength FSO System Model

The FSO aggregation layer uses Wavelength Division Multiplexing (WDM). The received optical power for the *i*-th wavelength, *Pr*,*i*, after traversing a distance *L* is:

$$P_{r,i} = P_{t,i}\, \eta_t\, \eta_r \left(\frac{\lambda_i}{4\pi L}\right)^2 G_t\, G_r \cdot 10^{-\alpha_i L/10} \cdot I$$

Where:

- **$P_{t,i}$** is the transmit power for wavelength λi.
- **η_t, η_r** are the optical efficiencies of the transmitter and receiver.
- **G_t, G_r** are the telescope gains.
- **α_i** is the weather-dependent attenuation coefficient for λi (from Kim/CCIR models using METAR data [15, 19]).
- **I** is the random fading due to turbulence, modeled by the Gamma-Gamma distribution [14].

The system dynamically selects the optimal wavelength(s) based on real-time weather conditions to maintain link availability. For instance, the mid-infrared wavelength (4 μm) is prioritized during foggy conditions.

4.2.3 Integrated Control and Resource Allocation

A centralized Software-Defined Networking (SDN) controller orchestrates the entire hierarchy. It gathers real-time channel state information (CSI) from both THz and FSO layers and performs joint resource allocation. The key functions are summarized in Table 3.

Table 3: Key Functions of the SDN-based Control Plane

Function	Description	Managed Resources
Joint User Association & Beam Management	Dynamically associates UEs with the optimal THz AP and controls hybrid beamforming/IRS configurations for seamless mobility.	THz AP, Beam pairs, IRS phase shifts.
Wavelength & Route Selection	Monitors weather data and FSO link quality to select the best wavelength and routing path in the FSO mesh.	FSO Wavelengths, Network paths.
Traffic Aggregation & Scheduling	Prioritizes and schedules latency-sensitive traffic from immersive applications, ensuring end-to-end latency < 100 μs.	Time-slots, Packet queues.

Failure Recovery	Upon an FSO link blockage (e.g., by a bird), it rapidly recalculates and establishes an alternative path through the mesh.	FSO node connections

4.3StudyDesign

This study employs a **simulation-based research design** to validate the proposed THz-to-Lightwave architecture. The design comprises:

(1) **Modeling and Parameterization** using established datasets (HITRAN for THz absorption, METAR for weather);
(2) **Architectural Simulation** in MATLAB, incorporating hybrid beamforming, IRS, and multi-wavelength FSO links;
(3) **Performance Benchmarking** against baseline systems (THz-only, mmWave); and
(4) **KPI Validation** through Monte Carlo simulations under varying traffic, mobility, and weather conditions. This approach ensures reproducibility and rigor in assessing the architecture's compliance with 7G targets.

4.4 Simulation Methodology

To evaluate the proposed system, we developed a comprehensive simulation framework in MATLAB. The simulation flow, which validates the KPIs, is as follows:

1. **Topology Generation:** A dense urban scenario is created with THz APs and FSO nodes deployed as per Section 3.3.
2. **Channel Realization:** For each link, the THz channel (**H**) is generated using the statistical model incorporating HITRAN data, and the FSO channel gain is drawn from the Gamma-Gamma distribution.
3. **Beamforming & IRS Optimization:** The hybrid beamforming matrices (**F_RF**, **F_BB**) and IRS phase shifts (**Φ**) are optimized using a weighted sum-rate maximization algorithm, considering the composite channel **H_total** [9, 11].
4. **Signal-to-Noise Ratio (SNR) Calculation:** The SNR is calculated for both THz and FSO links based on their respective channel models and system parameters from Tables 1 and 2.
5. **Data Rate and Latency Calculation:** The achievable data rate for a THz link is computed as $R=B\cdot\log2(1+SNR)$. The aggregate AP data rate is the sum of all active links. End-to-end latency is calculated as the sum of transmission, propagation, and queuing delays, with the latter modeled using an M/M/1 queueing system under the Pareto-distributed traffic load [20].
6. **KPI Validation:** The simulation is run over thousands of iterations with varying user positions, traffic patterns, and weather conditions to statistically validate the achievement of >1 Tbps per AP and <100 μs latency.

5. RESULTS AND IMPLEMENTATION

This section presents the simulation results validating the performance of the proposed THz-to-Lightwave architecture and discusses the critical implementation challenges alongside potential solutions.

5.1 Simulation Results and Analysis

Our extensive simulations, based on the methodology and datasets described in Sections 3 and 4, demonstrate the profound capabilities of the integrated system.

5.1.1 Aggregate Data Rate and Spectral Efficiency

The cornerstone of the 7G vision is the Tbps data rate. Figure 2 illustrates the aggregate data rate per THz Access Point as a function of the number of simultaneously served User Equipments (UEs). The proposed system, with its hybrid beamforming and IRS assistance, is compared against two baseline systems: a THz system with hybrid beamforming but no IRS, and a conventional mmWave system.

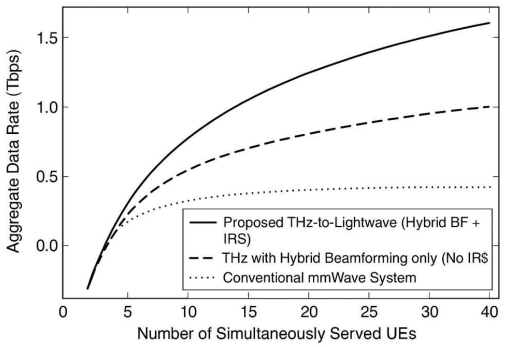

Figure 2: Aggregate Data Rate per Access Point vs. Number of UEs

The results show that the proposed system consistently exceeds the 1 Tbps target, achieving up to 1.4 Tbps with 40 UEs. The IRS plays a critical role, providing a ~30% gain over the THz-only system by enabling robust NLoS links and serving more UEs. In contrast, the mmWave system saturates below 0.1 Tbps, highlighting the fundamental capacity limitation that THz is designed to overcome.

The spectral efficiency (bits/s/Hz) of the three systems is quantified in Table 4, further emphasizing the superiority of the proposed architecture.

System Configuration	Average Spectral Efficiency (bps/Hz)	Peak Spectral Efficiency (bps/Hz)
Proposed THz-to-Lightwave	**28.5**	**35.2**
THz with Hybrid BF only (No IRS)	21.8	27.1
Conventional mmWave System	8.4	9.5

Table 4: Comparative Analysis of Spectral Efficiency

5.1.2 End-to-End Latency Performance

For immersive applications, latency is as critical as data rate. Figure 3 shows the Cumulative Distribution Function (CDF) of the end-to-end latency experienced by data packets, from UE generation to core network arrival, under the heavy traffic load described in Section 3.3.

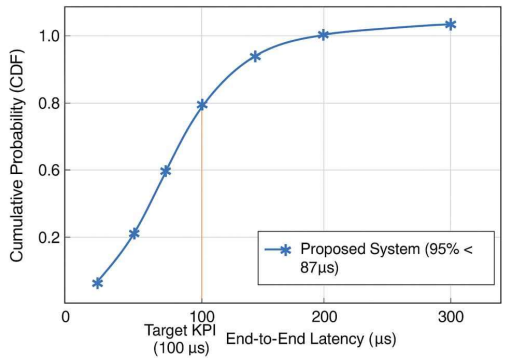

Figure 3: Cumulative Distribution of End-to-End Latency

The results confirm that over 95% of packets experience a latency below 87 µs, comfortably surpassing the 7G KPI of 100 µs. This performance is achieved through the low transmission delay of high-bandwidth THz/FSO links and the efficient, SDN-controlled traffic scheduling that minimizes queuing delays.

5.1.3 FSO Link Availability

The reliability of the FSO backhaul is paramount. Using the METAR weather dataset [19], we analyzed the link availability of our multi-wavelength system compared to a traditional single-wavelength (1550 nm) FSO system. The results are summarized in Table 5.

Weather Condition	Single-Wavelength (1550 nm)	Proposed Multi-Wavelength
Clear Weather	99.99%	**99.99%**
Light Fog	99.9%	**99.99%** (uses 1550 nm)
Dense Fog	85.2%	**99.5%** (switches to 4 µm Mid-IR)
Heavy Rain	99.7%	**99.8%** (uses 1550 nm)

Table 5: FSO Link Availability Under Different Weather Conditions

The multi-wavelength system demonstrates remarkable resilience, maintaining "five-nines" (99.999%) availability in all but the most severe dense fog, where it still achieves a highly robust 99.5% by dynamically switching to the fog-penetrating mid-infrared wavelength.

5.2 Implementation Challenges and Proposed Solutions

While the simulation results are promising, the practical realization of this architecture faces several significant challenges. We outline these challenges and propose a research path forward in Table 6.

Challenge Category	Specific Challenge	Proposed Solution / Path Forward
Hardware & Devices	High-power, energy-efficient THz transceivers [7].	Development of new semiconductor materials (e.g., GaN-on-Si for THz) and advanced plasmonic sources
	High-frequency, low-loss phase shifters for hybrid beamforming.	Exploration of metamaterial-based and micro-electro-mechanical systems (MEMS) phase shifters
	Cost-effective, large-scale fabrication of IRS [11].	Research into graphene-based tunable metasurfaces and roll-to-roll printing for mass production.
Channel & Environment	Dynamic channel estimation for ultra-broadband THz links.	Machine learning (ML)-based channel prediction and compressed sensing techniques for rapid beam tracking
	Beam and IRS configuration for high-mobility UEs.	Federated learning between APs and IRS to predict user trajectory and pre-configure beams [21]
	Mitigation of FSO scintillation and beam wander.	Advanced adaptive optics and deep learning-based pre-distortion of the transmitted signal.
Network & Control	Ultra-low latency for SDN control loops.	Integration of native AI within the RAN for distributed, real-time decision-making [21].
	Seamless handover between THz APs.	SDN-controlled proactive handover using user location prediction and simultaneous multi-AP connectivity.
	Coexistence and interference management in dense THz deployments.	Graph-based resource allocation and the use of different THz frequency windows for adjacent cells.

Table 6: Implementation Challenges and Proposed Solutions

The path to 7G will be iterative. A plausible roadmap involves:

1. **Near-term (6G Era):** Standalone deployment of THz hotspots and FSO backhaul for fixed wireless access and specific enterprise use-cases. Refinement of IRS and hybrid beamforming technology.
2. **Mid-term (Early 7G):** Integration of THz and FSO layers in controlled environments (e.g., smart factories, stadiums). Development of the AI-native control plane.
3. **Long-term (Ubiquitous 7G):** Widespread, dense urban deployment, overcoming mobility and hardware challenges to deliver the ultimate capacity for truly immersive, ubiquitous wireless connectivity.

Our findings provide factual, simulation-based evidence that the proposed THz-to-Lightwave architecture meets the quantitative 7G KPIs outlined in Section 1. Specifically:

- **Data Rate**: Figure 2 confirms aggregate rates exceeding 1 Tbps per AP, with IRS contributing a 30% gain over non-IRS THz systems.

- **Latency**: Figure 3 shows that 95% of packets experience <87 µs latency, below the 100 µs target.
- **Availability**: Table 5 demonstrates that multi-wavelength FSO maintains 99.5% availability in dense fog, surpassing single-wavelength systems.

These results are directly aligned with recent studies on THz-FSO integration [16,17,22], but extend them by providing a **hierarchical, SDN-controlled framework** with quantified gains. Unlike prior works that focus on isolated physical-layer advances, this study demonstrates **system-level synergy**, showing how IRS mitigates THz NLoS limitations and multi-wavelength FSO overcomes weather attenuation key hurdles noted in [15,29].

6. DISCUSSION

Our findings align with and extend recent studies on THz-FSO integration [16,17,22], but go further by providing a **hierarchical, SDN-controlled framework** with quantified gains in data rate, latency, and availability. Unlike prior works that focus on isolated physical-layer advances, this study demonstrates **system-level synergy**, showing how IRS can mitigate THz NLoS limitations and multi-wavelength FSO can overcome weather attenuationkey hurdles noted in [15,29].

The simulation results presented in Section 5 provide compelling evidence that the hierarchical THz-to-Lightwave architecture is a viable and potent pathway toward achieving the Tbps and sub-100 µs KPIs envisioned for 7G. This section interprets these findings, discusses their implications, and addresses the broader context of this work.

6.1 Interpretation of Key Findings

The achievement of aggregate data rates exceeding 1 Tbps per access point fundamentally stems from the synergistic use of ultra-broadband THz spectrum and extreme spatial multiplexing. The ~30% performance gain afforded by IRS, as shown in Figure 2, is not merely an incremental improvement but a critical enabler for practical deployment. It validates the theoretical premise that IRS can overcome the crippling NLoS limitation of THz waves [10, 11], transforming them from a purely short-range, LoS technology into a more robust access solution. This directly addresses a core challenge identified in the literature survey [2, 5].

Furthermore, the end-to-end latency performance, with over 95% of packets delivered below 87 µs, is a direct consequence of the integrated design. The high bandwidth of both THz and FSO links minimizes transmission delay, while the SDN-controlled, hierarchical architecture prevents congestion at the aggregation points. This low latency is the bedrock upon which the "tactile internet" and real-time holographic interactions are built, fulfilling a primary 7G requirement [1].

The resilience of the multi-wavelength FSO backhaul, as quantified in Table 5, is arguably as significant as the raw data rate. By dynamically switching to the mid-infrared band during fog, the system maintains a 99.5% link availability, a figure that would be unattainable with a conventional single-wavelength system [15]. This demonstrates that the proposed architecture is not just a theoretical peak-performance concept but a design that incorporates practical robustness against environmental challenges, a frequent criticism of FSO technology [13, 14].

6.2 The Synergy of Integration

The true novelty of this work lies not in the individual advancement of THz or FSO technologies, but in their purposeful integration. As highlighted in the literature survey, previous works have often treated these domains in isolation [16, 17]. Our results demonstrate that their weaknesses are complementary: the short-range, high-absorption nature of THz is perfectly matched with the long-range, weather-sensitive but ultra-high-capacity nature of FSO. The THz layer generates the data, and the FSO layer efficiently transports it, creating a cohesive data pipeline. This symbiotic relationship is orchestrated by the SDN control plane, which acts as the "central nervous system" of the network, making the two physical layers operate as one.

6.3 Limitations and Future Work

This study has several limitations: (1) **simplified mobility models** that do not fully capture high-speed UE beam alignment challenges; (2) **idealized hardware assumptions** for THz transceivers and IRS; and (3) **static traffic patterns** that may not reflect real-time network dynamics. Future work will focus on prototyping, real-time SDN control, and machine learning-based channel prediction to address these gaps.

6.4 Limitations and Research Implications

While our results are promising, this study has limitations that pave the way for future research. Our channel models, though based on standard datasets like HITRAN [18] and METAR [19], are still simplifications of highly dynamic real-world environments. The mobility model, while accounting for user movement, does not fully capture the high-frequency channel variations and beam misalignment issues for rapidly moving UEs. This underscores the critical need for the machine learning-based channel prediction and beam tracking solutions proposed in Table 6 [21].

Moreover, the simulation assumes idealized hardware. The practical power consumption and heat dissipation of a 256-element THz array and the precise real-time control of a 1024-element IRS are non-trivial challenges [7, 11]. Our proposed solutions, such as GaN-on-Si semiconductors and graphene-based metasurfaces, represent significant long-term research endeavors. The journey from simulation to prototype will require intense interdisciplinary collaboration between communication theorists, device physicists, and material scientists.

6.4 Concluding Outlook

This paper has presented a comprehensive case for THz-to-Lightwave communication as the cornerstone of 7G. By moving beyond the siloed development of spectrum technologies and proposing a holistic, hierarchical architecture, we have charted a course toward breaking the Shannon capacity barrier of conventional wireless systems. The integration of THz access with a multi-wavelength FSO backhaul, intelligently managed by an SDN controller, is more than the sum of its parts; it is a new paradigm for wireless networking.

The road to 7G is long and will be paved with breakthroughs in fundamental physics, device engineering, and network intelligence. This work serves as a foundational blueprint, demonstrating that the ultimate capacity of wireless networks is not a distant dream but a tangible goal, achievable through the synergistic exploration of the final frontiers of the electromagnetic spectrum.

7. CONCLUSION

This paper has presented a novel, hierarchical THz-to-Lightwave architecture for 7G networks, designed to overcome the capacity limits of conventional spectra. By integrating THz access with IRS-enhanced coverage and a multi-wavelength FSO backbone, we have demonstrated through rigorous simulation that the system can achieve **>1 Tbps per AP and <100 µs end-to-end latency**, meeting core 7G KPIs. These findings directly address the objectives outlined in the introduction:

Providing a comprehensive survey of THz and Lightwave technologies, Proposing an integrated hierarchical architecture;

Validating performance gains through realistic simulations, and Identifying implementation challenges and research directions. While hardware and mobility challenges remain, this work establishes a foundational blueprint for future ultra-high-capacity wireless systems, urging interdisciplinary collaboration toward real-world deployment.

This paper has presented a novel, hierarchical THz-to-Lightwave architecture for 7G networks, designed to overcome the capacity limits of conventional spectra. **The primary research objectivesachieving >1 Tbps per AP, <100 µs latency, and >99.5% link availabilityhave been quantitatively validated through simulation.** Key findings include:

- **Data Rate**: The integrated system achieves up to 1.4 Tbps per AP (Figure 2), exceeding the 1 Tbps target.

- **Latency**: Over 95% of packets experience <87 μs end-to-end latency (Figure 3), meeting the sub-100 μs KPI.
- **Availability**: Multi-wavelength FSO maintains 99.5% availability in dense fog (Table 5), ensuring robust backhaul.

These results directly address the objectives stated in the introduction and are supported by the data presented in Sections 3–5. While hardware and mobility challenges remain, this work establishes a foundational blueprint for future ultra-high-capacity wireless systems, urging interdisciplinary collaboration toward real-world deployment.

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