Evaluating the Maturity of 5G and the Rise of Optical/THz Architectures for 6G

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Abstract

5G was developed to address growing mobile traffic demands with higher spectral efficiency, multi-gigabit data rates, and low-latency access. While 5G delivers improvements over LTE, real-world performance falls short of early projections due to spectrum scarcity, RF propagation loss at higher frequencies, and the cost of network densification. These constraints are structural and limit the scalability of radio-only architecture. As global data consumption continues to accelerate, future networks are expected to transition toward optical wireless communication (OWC) and terahertz (THz) bands, which provide orders of magnitude more bandwidth and enable tightly directional links to reduce interference. Moreover, integrated sensing and communication (ISAC) architectures are emerging as a necessary enabler for device awareness, mobility robustness, and resource-efficient 6G operation. This paper evaluates the current maturity of 5G within its physical and infrastructural limitations and analyzes the role of optical and THz systems as foundational spectrum domains for functional 6G networks.

Introduction

Wireless networks have gone through four major generations over the last four decades, with each generation adding new capabilities and higher user data rates. First generation systems focused on analog voice. Second and third generations added digital modulation, basic data services, and mobile Internet. Fourth generation LTE and LTE Advanced introduced packet based broadband access and large-scale multiple input multiple output (MIMO) with orthogonal frequency division multiplexing (OFDM) to push spectral efficiency much closer to Shannon limits in sub 6 GHz bands.

5G was defined to extend this trajectory by exploiting higher carrier frequencies, wider bandwidths, and more aggressive spatial reuse. Early visions of 5G emphasized three broad service classes: enhanced Mobile Broadband (eMBB), ultra reliable low-latency communications (URLLC), and massive machine type communications (mMTC). To support these classes, 5G New Radio (NR) introduced flexible numerologies, scalable slot durations, and support for mmWave spectrum together with massive MIMO and beamforming.

The technical literature shows that mmWave cellular operation is feasible and can deliver very high data rates when combined with directional antennas and dense deployment [1], [2]. However, propagation loss, blockage, and rain attenuation at these frequencies impose strict constraints on cell radius and infrastructure layout [1]. These are not implementation bugs that can be patched out of the system. They arise from fundamental propagation physics and the realities of urban environments.

At the same time, there is a growing body of work arguing that radio alone is not sufficient to sustain capacity growth into the 2030s. OWC can exploit the enormous unlicensed optical spectrum for short-range, high-capacity links, particularly in indoor and controlled environments [3]. THz communication promises similar capacity gains in the 0.1–10 THz band, with very high directionality and extremely wide contiguous bandwidths, but also with strong constraints from molecular absorption and hardware limitations [4]. While early 6G vision papers remain somewhat high level, they consistently assume that future networks will integrate these new spectrum domains into a heterogeneous architecture [5].

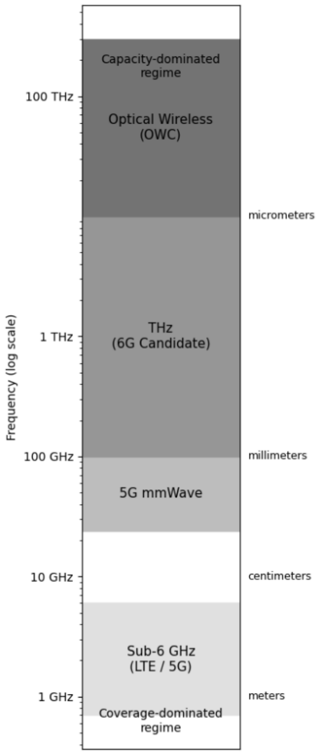

Figure 13. Conceptual evolution of wireless spectrum utilization from LTE and sub-6 GHz systems through 5G mmWave and prospective 6G operation in the terahertz and optical domains.

There is a conceptual shift from "networks that only communicate" to "networks that communicate and sense". ISAC intentionally uses the same waveform, spectrum, and hardware to support both data transmission and environmental sensing functions, enabling new capabilities in vehicular networks, perceptive mobile networks, and cross layer resource management [6].

This paper has three goals:

1. Evaluate the current maturity of 5G in terms of the gap between theoretical capability and practical deployment.

2. Identify structural limits that prevent 5G from scaling indefinitely through RF refinements alone.
3. Analyze how OWC, THz communication, and ISAC orient the design space for 6G architectures.

Background on 5G Architecture and Spectrum Use

5G NR was deliberately designed as a spectrum-agnostic air interface operating across multiple frequency ranges to combine broad coverage with regional capacity expansion

<u>5G Spectrum Layers</u>

Rappaport et al. identify three dominant 5G spectrum regions [1]:

- Sub 6 GHz bands (Frequency Range 1, FR1), including both legacy LTE bands and new mid band allocations.
- mmWave bands (Frequency Range 2, FR2), typically around 24–40 GHz and in some regions higher.
- Unlicensed and shared bands that support supplemental downlink or localized deployments.

Rappaport et al. emphasize the role of mmWave at 28 and 38 GHz as the primary innovation that allows 5G to escape the bandwidth limitations of the 700 MHz to 2.6 GHz legacy cellular allocations [1]. At these mmWave frequencies, channel bandwidths of the order of 1 GHz become realistic, which directly translates to much higher peak data rates.

Rangan et al. extend this view with network level simulation work showing that mmWave systems can offer roughly a twenty-fold increase in overall cell capacity compared to state of the art LTE when wide bandwidths and directional antennas are used [2]. However, they also show that these systems operate in a regime where many users are limited by thermal noise and outage, rather than by interference, particularly at cell edges [2]. This distinction has critical consequences for network architecture and for how far 5G can scale by "more of the same".

5G NR and RAN Architecture

5G NR introduces flexible numerologies with scalable subcarrier spacing and slot duration. This allows the same air interface to operate in low bands, mid bands, and mmWave bands with different tradeoffs between latency, Doppler tolerance, and implementation complexity.

On the RAN side, the move toward centralized and cloud-based radio access networks is already under way. 5G C-RAN architectures group baseband units in centralized pools, while remote radio heads provide the RF front ends distributed across the coverage area. High capacity and low-latency fronthaul links, often based on optical fiber, connect the base band unit (BBU) pool to the radio heads [6]. This centralization is not just an implementation choice. It directly supports coordination in both communication and sensing functions as later discussed.

However, a large fraction of deployed 5G networks are still based on non-standalone architectures where 5G NR radios are anchored to LTE cores. This limits the practical realization of URLLC and full network slicing, even though the air interface itself supports the required numerologies and scheduler behavior.

Maturity and Structural Limits of 5G

Although 5G base stations and devices are commercially available worldwide, maturity must be evaluated not only by standard completion but also by how well the system performs under real deployment constraints.

mmWave Propagation and Cell Radius

Extensive measurement campaigns in urban environments confirm that mmWave performance is strongly dependent on maintaining line-of-sight. Rappaport et al. observed line-of-sight (LOS) path loss exponents between 2.3 and 2.6, approximately consistent with free-space expectations when beams are aligned properly [1]. However, non-line-of-sight (NLOS) exponents above 5 introduce rapid decay, leading to coverage holes from transient obstacles such as vehicles or human bodies. Penetration losses of 30–40 dB through brick and coated glass severely restrict outdoor-to-indoor signal coupling [1]. Consequently, practical mmWave cell radii are typically in the range of 100–200 meters under ideal deployment conditions.

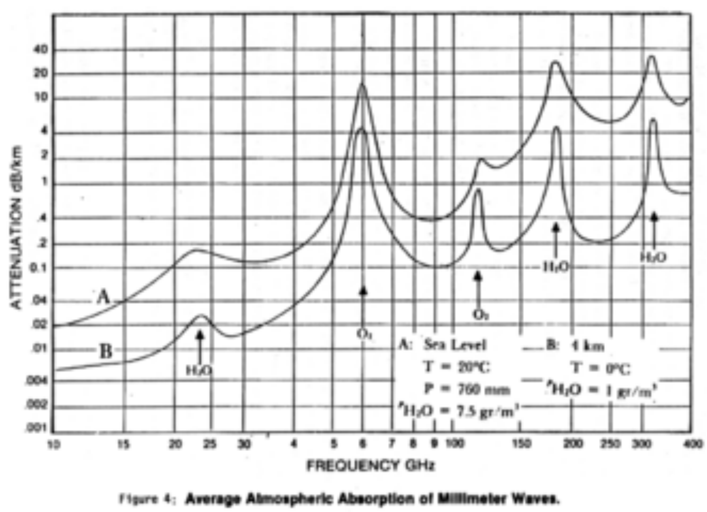

Figure 14. Atmospheric attenuation of millimeter-wave signals illustrating intrinsic absorption peaks and transmission windows that constrain practical mmWave cellular operation. Source: Federal Communications Commission (public domain).

These are not temporary early-deployment issues. They are governed by the physics of short-wavelength propagation.

Noise Limited Behavior and Directional Isolation

In many current sub 6 GHz networks, performance is limited by interference. Cells reuse spectrum aggressively, and the network is noise limited only in special situations. In contrast, Rangan et al. observe that mmWave small cells can operate in regimes where many links are limited by thermal noise and bandwidth rather than by interference [2]. Interference to noise ratios are often modest because highly directional beams isolate many links in angle [2].This is both an advantage and a challenge. It relaxes some of the pressure to deploy complex interference coordination and advanced coordinated multipoint techniques, but it also implies that adding more base stations does not automatically improve the experience of users who are already noise limited and close to the edge of coverage.

Economic and Infrastructural Constraints

The viability of mmWave is further restricted by cost. Each small cell requires fiber-class fronthaul to support multi-gigabit traffic; backhaul availability remains uneven and expensive to deploy. Sites require power distribution, physical mounting, security, and ongoing maintenance. On the device side, phased array beamforming increases the thermal and power demands of smartphones.

Because of these systemic constraints, most operators prioritize mid-band deployments that offer moderate performance improvements with fewer infrastructure burdens. In this sense, 5G is technologically mature but architecturally bounded.

Optical Wireless Communication as a 6G Building Block

Basic Concepts and System Types

OWC uses optical carriers in the infrared, visible, or ultraviolet bands to transmit data through free space. Alsulami et al. categorize OWC systems into several classes, including visible light communication, infrared indoor systems, outdoor free space optical links, and hybrid RF–optical systems [3]. These systems share several features that are relevant for a 6G context:

- Very large available bandwidth compared to RF, often tens or hundreds of terahertz.
- Highly directional beams with narrow divergence, leading to high spatial reuse and inherent physical layer security.

- Sensitivity to atmospheric conditions such as fog, rain, and turbulence in longer outdoor paths.

OWC is already used in niche applications such as indoor LiFi and long-distance free space optical backhaul. The question for 6G is how far these concepts can be pulled into mainstream mobile and edge networking.

Advantages Relative to RF

Several advantages make OWC a compelling complementary technology to RF systems. The most significant distinction is the enormous bandwidth available in the optical domain. Even after accounting for practical modulation limits, the usable optical spectrum exceeds RF allocations by several orders of magnitude, allowing short-range links to support multi-tens-of-gigabits per second when transmitter and receiver alignment is maintained [3]. OWC links are also highly directional, which inherently reduces interference and enables dense spatial reuse in confined or structured environments such as offices, data centers, or factory floors. Because optical carriers operate in unlicensed portions of the spectrum, deployment avoids many of the licensing and regulatory constraints associated with RF systems, reducing barrier for enterprise-scale adoption. In addition, OWC links do not contribute to RF congestion and are electromagnetically compatible with environments where RF emissions must be limited. Collectively, these properties position OWC as an attractive ultra-broadband access mechanism that augments, rather than replaces traditional RF layers.

Constraints and Integration Challenges

Because OWC relies on near-line-of-sight propagation, its performance is highly sensitive to environmental factors such as fog, dust, and human obstruction [3]. Variations in device orientation and user mobility further complicate link management. As a result, OWC is most effective when deployed as a localized ultra-broadband access layer that complements existing RF infrastructure rather than serving as a standalone replacement.

Terahertz Communication and its Role in 6G

THz Spectrum and Channel Characteristics

The terahertz band, typically defined between 0.1 and 10 THz, occupies the transitional region between millimeter-wave frequencies and the infrared optical domain. Akyildiz et al. emphasize that this band contains several contiguous spectral windows with comparatively low molecular absorption, making it possible to allocate extremely wide bandwidths on the order of tens of gigahertz [4]. These windows, however, are interspersed with absorption peaks caused primarily by water vapor and other atmospheric molecules, producing a highly frequency-selective propagation environment whose characteristics vary with humidity and transmission distance. THz propagation is inherently directional due to the very short wavelengths, with limited diffraction and a strong reliance on line-of-sight paths. As a result, THz links can support exceptionally high data rates over short distances but remain highly sensitive to blockage, alignment errors, and environmental fluctuations. These properties position the THz band as a unique intermediate regime between RF and optical communication, offering substantial capacity benefits within constrained spatial and environmental conditions.

Potential Application Domains

The unique propagation characteristics and wide bandwidth availability of the THz band enable several specialized application domains relevant to early 6G architectures. Akyildiz et al. highlight its suitability for high-speed wireless backhaul and fronthaul, particularly in dense small-cell networks where fiber access is limited or expensive to deploy [4]. THz links also show promise for device-to-device communication in data centers and high-performance computing systems, where cable management is complex and line-of-sight paths can be engineered by design. Beyond infrastructure, short-range THz access points may support emerging applications such as ultra-high-resolution augmented reality, holographic communication, and interactive kiosk-based data offloading. Across these scenarios, THz is not positioned as a universal access technology but rather as a complementary layer that provides extreme throughput in environments where line-of-sight conditions and alignment can be reliably maintained.

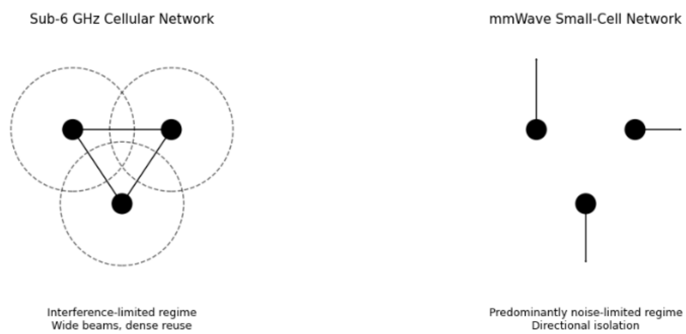

Figure 15. Conceptual comparison of interference-limited operation in sub-6 GHz cellular networks and predominantly noise-limited operation in directional mmWave deployments.

Hardware and System Challenges

Despite rapid advances in THz research, significant hardware and system-level challenges remain before widespread deployment becomes feasible. Current THz transmitters and receivers often rely on frequency multiplication, photomixing, or other non-integrated methods that result in low power efficiency and increased complexity [4]. Antenna design at THz frequencies requires highly precise manufacturing tolerances, while the associated analog and mixed-signal front ends must handle extremely wide instantaneous bandwidths without sacrificing noise performance or linearity. These hardware limitations mirror, but substantially amplify, the challenges encountered during the development of mmWave 5G systems. From a network perspective, THz communication inherits the need for rapid beam training, continuous alignment, and robust blockage mitigation, all of which become more difficult as carrier frequency increases. Therefore, although THz communication holds significant promise, its role in 6G networks will likely be confined to scenarios where the physical environment and user mobility can be carefully managed.

6G and the Need for Integrated Architectures

Hight Level 6G Objectives

Saad, Bennis, and Chen outline a vision of 6G systems that goes beyond incremental throughput gains, highlighting applications such as immersive extended reality, connected robotics, pervasive intelligence, and holographic communications [5]. These emerging use cases impose requirements that cannot be met by incrementally improving current RF architectures. For example, real-time robotic control and industrial automation require sub-millisecond end-to-end latency, while holographic or volumetric communication demands aggregate capacity far beyond the peak rates of contemporary networks. In addition, the expected density of sensors, actuators, and autonomous agents means that future systems must manage not only higher data rates but also more complex computational and control tasks distributed across the network. This broader vision suggests that 6G will integrate communication, computation, control, and caching in a unified framework, supported by edge intelligence and a diverse set of spectrum domains that extend beyond traditional RF. Optical wireless communication, THz bands, and advanced mmWave systems all appear as foundational components within this emerging design landscape.

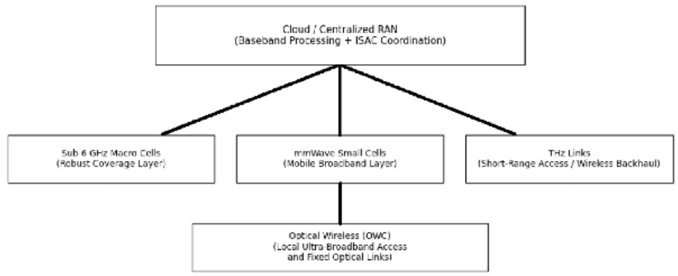

Figure 16. Conceptual heterogeneous 6G network architecture integrating sub-6 GHz macro cells, mmWave small cells, terahertz links, and optical wireless systems, coordinated through a centralized cloud-RAN framework.

<u>Perceptive Mobile Networks and ISAC</u>

Liu et al. propose that integrated sensing and communication (ISAC) will serve as a defining capability of 6G networks, enabling systems that simultaneously transmit data and perceive their surrounding environment through shared hardware, spectrum, and waveform resources [6]. The advantage of ISAC arises partly from integration gain, in which sensing and communication functions reuse the same physical-layer infrastructure, and partly from coordination gain, in which sensing information directly improves communication performance. In cloud-RAN architectures, centralized baseband units can aggregate sensing returns from distributed radio heads connected by high-capacity fronthaul links, enabling both monostatic and bistatic sensing operations. These architectures allow the network to interpret reflections, Doppler shifts, and other physical-layer features to infer object positions, mobility patterns, and environmental geometry. Such capabilities can support more efficient beam training, faster handover decisions, dynamic resource allocation, and improved physical-layer security. Importantly, the short wavelengths and narrow beams of mmWave and THz systems naturally enhance spatial sensing resolution, making ISAC not an incremental addition but a necessary mechanism for maintaining reliable and low-latency communication at higher frequencies.

Sensing Assisted Communications

Liu et al. discuss several concrete scenarios where sensing information improves communication performance, especially in vehicular networks [6]:

- Sensing assisted beam training and tracking, where an RSU uses radar like returns from vehicles to predict angle of arrival and departure, reducing the pilot and feedback overhead associated with beam sweeps.
- Sensing assisted resource allocation, where range, velocity, and geometry estimates inform spectrum, power, and beamwidth allocation across vehicles to manage interference and maintain quality of service.
- Sensing assisted physical layer security, where location and motion information about potential eavesdroppers allows BSs to design directional beams and artificial noise patterns more effectively.

These are not speculative addons. They become almost mandatory when operation shifts to high frequency bands where beam misalignment and blockage can quickly destroy link quality. ISAC therefore links the physical characteristics of mmWave and THz with the higher-level goals of 6G.

Discussion: From 5G limitations to 6G design Principles.

Taken together, the results from sections III through VI illustrate that 5G should be viewed as a transitional platform rather than an end point. While 5G introduces mmWave operation, flexible numerologies, and early cloud-RAN concepts, its performance in practical deployments is fundamentally constrained by propagation physics, infrastructure cost, and noise-limited behavior at higher frequencies. These limitations define a natural boundary on how far traditional RF-centric design can scale. The emerging body of work on OWC and THZ communication suggests that future systems will require a multilayer spectrum strategy in which each band is used where its strengths dominate: sub-6GHz for robust coverage, mid-band and mmWave for mobile broadband, OWC for ultra-high-capacity indoor links, and THz for short-range or backhaul scenarios. ISAC adds an additional dimension by coupling communication and sensing, allowing networks to leverage environmental awareness to support beam alignment, resource allocation, and mobility management capabilities that become essential at high frequencies. Collectively, these insights point towards 6G architectures that blend heterogeneous spectrum resources with centralized coordination and sensing-assisted intelligence, moving the network from a purely communicative systems toward a perceptive, adaptive, and integrated platform.

Future Directions: Attojoule Optoelectronics for 6G Processing and Interconnects

The architectures envisioned for 6G rely not only on new spectrum domains but also on substantially more capable baseband and edge processing platforms. Massive MIMO, ISAC, and heterogeneous RF–OWC–THz operation all require large-scale matrix operations, high-rate FFTs, and low-latency machine learning inference at the network edge. Conventional electronic processors and interconnects face fundamental energy and bandwidth limitations in this regime. Miller's analysis of attojoule optoelectronics suggests that future information processing and communication systems may need to approach energy costs on the order of tens of femtojoules or below per bit to remain scalable [7]. This perspective motivates the use of optoelectronic modulators, photodetectors, and optical interconnects that satisfy stringent material criteria on absorption contrast and index change while maintaining low background loss and short device lengths.

At the system level, dense free-space and guided-wave optical interconnects can support large numbers of spatial channels between chips or boards within a limited aperture, enabling multi-terabit-per-second communication inside data centers, baseband pools, or edge computing clusters [7]. Such interconnects align naturally with cloud-RAN and centralized 6G architectures, where fronthaul, midhaul, and intra-rack links risk becoming bottlenecks if they remain purely electronic. While these optoelectronic platforms are not themselves access technologies in the same sense as OWC or THz links, they can serve as key enablers for the computational and interconnect fabric that underpins 6G operation. In this sense, attojoule-scale optoelectronics and optical interconnects represent a complementary research direction that must progress in parallel with spectrum-domain innovation.

Conclusion

5G introduced mmWave operation, flexible numerologies, and early cloud RAN concepts into commercial networks. Measurements and analysis show that mmWave 5G can deliver large capacity gains in dense small cell deployments with directional beamforming [1, 2]. However, propagation loss, blockage, building penetration, and backhaul constraints limit its scalability as a universal solution. These constraints are inherent to RF physics and urban geometry, not simply misconfigurations.

Looking forward, OWC and THz technologies offer orders of magnitude more bandwidth, narrow beams, and high spatial reuse for specific scenarios [3, 4]. At the same time, 6G vision work points toward networks that integrate computation, control, and communication, operating across multiple spectrum domains and leveraging edge

Taken together, these developments indicate that the path beyond 5G will involve a heterogeneous architecture that combines sub 6 GHz, mmWave, OWC, and THz with integrated sensing and cloud-based coordination. 5G can be seen as the first large scale step in this direction, but the full realization of 6G capabilities will require deeper integration of new spectrum domains and sensing functionalities into the core design of wireless networks.

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