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Building the Fabric of 6G:
Spectrum Frontiers and Enabling Technologies

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1. Executive Summary

The transition to 6G represents not an incremental improvement but a fundamental leap in mobile technology. Unlike previous generations, which primarily focused on speed and connectivity, 6G is envisioned as an **intelligent, immersive, and adaptive network fabric** that seamlessly integrates the physical, digital, and biological worlds. With early commercialization expected around 2030, 6G will enable applications such as **holographic telepresence, extended reality (XR), digital twins, and ultra-precise sensing,** all demanding gigabit-per-second data rates, sub-millisecond latency, and unprecedented reliability.

This paper explores the spectrum frontiers and enabling technologies that will define the 6G era. It highlights the strategic roles of each frequency range:

- **Sub-7 GHz (FR1):** The foundational coverage layer ensuring reliability, mobility, and inclusivity.
- **7–24 GHz (FR3):** The emerging capacity layer, balancing reach and throughput, and expected to become the workhorse of nationwide 6G deployments.
- **24–100 GHz (mmWave):** The augmentation layer delivering extreme capacity for dense urban hotspots, private networks, and fixed wireless access.
- **>100 GHz (Sub-THz and THz):** The transformative frontier enabling terabit-class links and integrated sensing for next-generation applications like holography and ultra-immersive XR.

Beyond access, **backhaul emerges as a strategic pillar**, with fiber as the anchor, complemented by RF (E-/D-band, sub-THz) and optical wireless (FSO/LiFi). The UAE's world-leading **fiber-to-the-home (FTTH) penetration**, driven by e& UAE's nationwide investment, provides a unique foundation for **fiber-first backhauling**—an advantage that few countries can replicate.

The paper also emphasizes **key enablers** including AI-native RANs, reconfigurable intelligent surfaces (RIS), extra-large MIMO, and integrated sensing and communication (ISAC). These technologies will stretch spectrum efficiency, ensure resilience, and embed sustainability into 6G by design.

On the regulatory front, global alignment through **WRC-23, WRC-27, and WRC-31** will be critical. The UAE, through the TDRA's proactive leadership, has already positioned itself at the forefront—being among the first to allocate the 6 GHz and 600 MHz bands, support FR3 trials, and plan early sub-THz pilots.

A landmark initiative highlighted in this paper is the **partnership between NYU Abu Dhabi and e& UAE** to demonstrate the **first Terahertz (THz) 6G pilot in the Middle East,** targeting unprecedented throughput and showcasing the UAE's role **as a global technology innovator.**

The **action agenda for the next 24–36 months** is clear:

- Secure harmonized FR3 spectrum and advance field trials.
- Right-size mmWave deployments using AI-driven orchestration.
- Pilot THz responsibly, focusing on validated spectrum windows.
- Expand hybrid backhaul, with fiber as the anchor.
- Embed sustainability and security into every spectrum layer.
- Contribute data and leadership to international standardization.

In conclusion, **6G will be defined by the co-design of spectrum, enabling technologies, and hybrid backhau**l, not by any single frequency band. For the UAE, with its early spectrum leadership, unmatched fiber foundation, and pioneering academic–industry partnerships, the path is clear: to position itself as a **global leader in shaping and delivering the 6G era.**

2. Introduction

Across the past three decades, each generation of mobile technology has acted as a catalyst of transformation. **2G** digitized voice, **3G** mobilized the internet, **4G** unlocked true mobile broadband, and 5G brought gigabit-class connectivity while supporting massive IoT and mission-critical services. Now, as the industry advances toward the **sixth generation (6G**), with early commercialization expected around 2030 and standardization already underway, the expectations are not for incremental progress but for a **fundamental leap**.

6G is envisioned as an **intelligent, immersive, and adaptive network fabric** that blurs the boundary between the physical, digital, and biological worlds. Its transformative potential is illustrated by use cases such as **extended reality (XR) with multi-sensory holograms, holographic telepresence, and large-scale digital twins** of cities, industries, and even human bodies. These applications demand terabit-per-second data rates, sub-millisecond latency, ultra-high reliability, and precise synchronization — requirements that translate directly into unprecedented spectrum needs.

The story of spectrum evolution mirrors this journey. For decades, mobile connectivity was anchored in **sub-7 GHz frequencies (FR1)**, delivering wide-area coverage but limited capacity. With 5G, the industry took its first bold step into **millimeter-wave (FR2, 24–100 GHz)**, proving the ability to deliver multi-gigabit rates but exposing trade-offs such as limited range and susceptibility to blockage. 6G will **therefore pivot to Frequency Range 3 (FR3, 7–24 GHz)** as the emerging "sweet spot" for macro-capacity, balancing coverage and throughput at scale. Beyond FR3, the **sub-THz and THz frontier (100 GHz–1 THz)** opens vast contiguous bandwidths essential for holography, ultra-immersive XR, and high-resolution sensing, while **optical wireless links** such as Free-Space Optics (FSO) will complement these by delivering fiber-like backhaul performance. Together, these bands form a **multi-layer spectrum fabric** where each layer contributes a distinct role: foundational coverage, scalable capacity, or transformative high-value services.

At the same time, enabling technologies will redefine what spectrum can achieve. **Extra-large MIMO arrays, reconfigurable intelligent surfaces (RIS), AI-driven beam management, and integrated sensing and communication (ISAC)** will extend the performance of each band beyond its physical limitations. The radio access network (RAN) itself will evolve toward **cell-free, distributed, and AI-native architectures,** ensuring spectrum layers are orchestrated as one adaptive system.

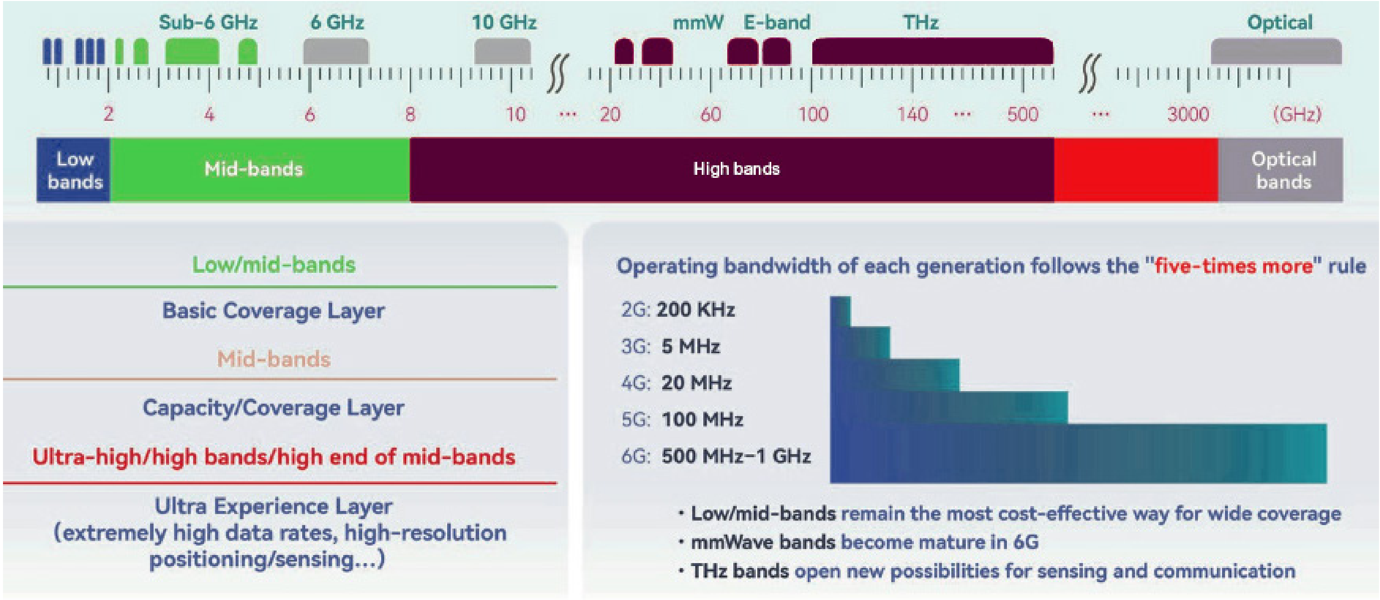
Equally important are the broader imperatives shaping 6G spectrum strategy. **Digital sustainability** will require energy-efficient spectrum use, green architectures, and AI-optimized operations to reduce carbon footprint. **Security and resilience** must be embedded by design, as different bands present distinct vulnerabilities: FR3 may be more exposed to jamming, while THz introduces novel risks in beam alignment and interception. **Private 6G networks** will emerge across enterprises and industries, leveraging localized FR3 or sub-THz spectrum for tailored deployments in factories, ports, and campuses, and will complement 5G private networks.

Finally, **the regulatory and strategic landscape** is already shifting. The outcomes of **WRC-23**, including the identification of the **6.425–7.125 GHz band for IMT**, mark the first globally harmonized new mid-band allocation in years. The UAE's **Telecommunications and Digital Government Regulatory Authority (TDRA)**, as host of WRC-23, played a pivotal role and has already moved to allocate the 6 GHz band, positioning the nation at the forefront of 6G spectrum adoption.

This paper, therefore, **maps the spectrum frontiers for 6G** across all layers:

- **Spectrum below 7 GHz (FR1)** as the foundational coverage anchor,
- **FR3 (7–24 GHz)** as the emerging capacity layer,
- **mmWave (24–100 GHz)** as the high-band augmentation layer,
- **Sub-THz and THz (>100 GHz)** as the transformative frontier.

In addition, it explores the critical role of backhaul innovations **(fiber, RF, and optical wireless),** examines **global spectrum policy and standardization developments**, and outlines **a forward-looking 6G spectrum roadmap.** By weaving together spectrum evolution, enabling technologies, regulatory perspectives, and sustainability imperatives, it highlights how 6G can emerge as **an intelligent, immersive, secure, and sustainable communication fabric** for the digital era ahead.



- Low/mid-bands remain the most cost-effective way for wide coverage
- mmWave bands become mature in 6G
- THz bands open new possibilities for sensing and communication

Figure 1: Multilayered frequency band framework: From Radio to Lightwave [1]

3. Spectrum Below 7 GHz: The Foundational Coverage Layer

The spectrum below 7 GHz, known in 3GPP as FR1, has always formed the foundation of mobile networks. It is the range that carried our voices with 2G, brought mobile internet with 3G, enabled broadband mobility with 4G, and provided the coverage anchor of 5G. Its value lies in qualities no other band can match: wide-area reach, strong indoor penetration, and robust mobility.

As 6G emerges, FR1 will continue to serve as the **coverage and control anchor,** ensuring that higher-frequency layers — FR3, mmWave, and (Sub)THz — can scale effectively.

3.1 Low Bands (600 -900 MHZ)

- **Coverage and Propagation**

The low bands are the quiet giants of mobile communication. Operating at 600–900 MHz, they spread across vast landscapes, with cell radii extending to multiple kilometers. Their long wavelengths bend gracefully around hills, cut through forests, and seep into basements, bringing connectivity to places where higher bands would falter. This makes them indispensable for rural coverage, suburban continuity, and deep-indoor penetration.

- **Capacity and Performance**

Yet this remarkable reach comes with inherent limits. With channels often just 5–20 MHz wide, the amount of data they can carry is modest compared to higher bands. Devices require larger antennas at these frequencies, restricting how many spatial streams can be supported. And because a single low-band cell can cover such wide areas, interference at the edges of the cell often constrains efficiency. These bands are not built for speed, but for resilience.

- **Use Cases & Applications**

Their strength lies in **reliability**. Low bands ensure that critical services such as emergency communications remain available, even when higher layers are overloaded or blocked. They provide **the control and signaling channels** that coordinate the broader spectrum fabric of the network. And they support massive IoT deployments in agriculture, utilities, and logistics, where devices need to transmit small amounts of data over long distances.

- **Deployment Outlook:**

As older technologies sunset, the refarming of 2G and 3G bands will release valuable sub-1 GHz spectrum for modern air interfaces. Discussions at **WRC-23** about reallocating portions of the **470–694 MHz** UHF band hint at a future where even broadcast spectrum could contribute to mobile services. In 6G, these bands will remain essential, ensuring that the farthest corners of society are not left behind.

TDRA has officially allocated the 600 MHz band for IMT in its updated National Frequency Plan, positioning it alongside 6 GHz to enable broader, more reliable coverage as part of the UAE's smart-city and future 5G / 6G ambitions. e& UAE has already carried out field tests using the 600 MHz spectrum, demonstrating that 5G coverage can extend beyond 6 kilometers when using suitably deployed networks and commercial-grade equipment. These efforts underscore a dual strategy: using low-band spectrum for wide reach and deep indoor penetration, while higher bands provide high speeds and capacity.

3.2 Lower Mid- Bands (1-7 GHZ)

- **Coverage and Propagation**

Climbing higher, the 1–7 GHz range has long been the workhorse of mobile broadband. These frequencies strike a delicate balance: they propagate well enough to cover wide areas while offering sufficient bandwidth to deliver meaningful capacity. At 3.5 GHz, cells can still span one to three kilometers in urban areas, and signals remain strong enough to penetrate indoors. Even at 6–7 GHz, propagation is still favorable for macro-cell deployments, unlike the sparse and fragile nature of mmWave.

- **Capacity and Performance**

Where the low bands provide reach, the mid-bands deliver **capacity.** Today, they support channels up to 100 MHz, but in 6G, they will expand toward 200–400 MHz. Combined with **Massive MIMO arrays** — scaling from 64T in 5G to 128 or even 256T in 6G — they will serve dozens of users simultaneously, with per-cell throughput reaching multi-gigabit levels. Multipath in this range remains rich, enabling robust MIMO performance, while latency and reliability targets align with 6G's demands.

- **Use Cases & Applications**

These frequencies will continue to underpin **urban and suburban broadband**, offering a balance of reach and capacity that makes them indispensable. They are also prime candidates for **enterprise connectivity**, supporting factories, campuses, and IoT-heavy environments where both reliability and throughput are needed.

- **Deployment Outlook**

The story of these bands is one of **renewal.** Legacy holdings at 1.8 and 2.1 GHz, once the backbone of 3G, are being repurposed for 5G and will transition into 6G. **Dynamic Spectrum Sharing (DSS)** will help operators smooth the coexistence of multiple generations. At the same time, **coordination techniques** such as CoMP **(Coordinated Multipoint Transmission/Reception)** and cell-free MIMO will link signals from multiple sites, improving edge performance and delivering a more consistent user experience.

3.3 Upper 6 GHz Band (6.425–7.125 GHz)

- **Regulatory Milestone**

The upper 6 GHz band represents a new milestone in spectrum policy. At **WRC-23,** regulators across EMEA, APAC, and parts of Latin America agreed to allocate the 6.425–7.125 GHz range for IMT, creating the first globally harmonized 700 MHz block in years. This decision marks a turning point, bridging the well-established FR1 mid-bands with the emerging FR3 range.

- **Coverage and Propagation**

In technical terms, the upper 6 GHz behaves like a bridge between mid-band and cmWave. Signals lose around 10 dB more through walls than at 3.5 GHz, but unlike mmWave, they can still reach indoors from outdoor macrocells. Urban coverage radii typically range from hundreds of meters to about two kilometers, striking a practical compromise between reach and throughput.

- **Capacity and Performance**

This band is where **capacity meets reach.** With up to 320 MHz of contiguous bandwidth, it enables multi-gigabit rates that approach mmWave performance but with far better coverage. Advanced Massive MIMO, with 128+ elements, enhances both peak and edge performance. Trials already show its potential: **Etisalat in the UAE achieved 10 Gbps throughput** by aggregating the 6 GHz band with existing holdings, a demonstration of both technological maturity and regional leadership.

- **Deployment Outlook**

The upper 6 GHz will layer onto existing macro grids, complementing C-band deployments and serving as a natural stepping stone into FR3. For many operators, it will be the first major 6G allocation to enter commercial use, enabling high-capacity services without requiring the densification of mmWave.

In the UAE, the Telecommunications and Digital Government Regulatory Authority (TDRA) has moved decisively to implement the outcomes of WRC-23 by formally including the 6 GHz spectrum band for IMT in its updated National Frequency Plan, with operations slated to begin between 2025-2026. Complementing this regulatory action, e& UAE has already conducted commercial-grade testing of the 6 GHz band, achieving ultra-fast speeds of up to 10 Gbps when aggregated with existing FR1 bands using CPE (Customer Premises Equipment) and demonstrating the band's potential for both high capacity in urban areas and useful indoor reach. Together, TDRA's spectrum allocations and e& UAE's real-world performance trials mark substantive progress toward bringing the upper 6 GHz band into commercial use, bridging mid-band 5G and preparing the groundwork for 5G-Advanced and, in due course, 6G services.

3.4 Cross-Layer Evolutionary Trends

The progression of FR1 into 6G is shaped by three converging trends. **Refarming** will gradually free spectrum below 2 GHz as legacy technologies retire, ensuring valuable low-band resources are modernized. **Integration of new allocations,** particularly the upper 6 GHz, will expand the FR1 portfolio and provide a critical capacity uplift. And **advances in radio technology** — extra-large MIMO, AI-driven spectrum management, and energy-aware optimization — will continue to stretch the efficiency of these frequencies.

3.5 Strategic Role

FR1 will remain the **cornerstone of reliability and inclusivity** in 6G. It is the spectrum that ensures everyone, everywhere, stays connected — whether in dense cities, remote villages, or deep indoor environments. Its wide coverage makes it inherently energy efficient, and AI-driven power control will further reduce energy per bit, aligning with global sustainability goals. As the anchor for control signaling, it must also be the most secure layer, hardened against jamming and spoofing with quantum-resistant cryptography and AI-based anomaly detection. And as regulators explore local licensing, FR1 will extend its role into **private 6G networks**, enabling enterprises and industries to harness wide, dependable coverage.

In sum, the spectrum below 7 GHz will not fade into the background of 6G. Instead, it will remain the **foundation upon which the higher layers rest**, ensuring that the ambitious goals of FR3, mmWave, and THz can be achieved with reliability, sustainability, and inclusivity.

4. Spectrum Between 7–24 GHz (FR3): The Emerging Capacity Layer

Among the new spectrum frontiers, **Frequency Range 3 (FR3**) — spanning 7 to 24 GHz — has emerged as the sweet spot for 6G. It balances the wide coverage of FR1 with the vast bandwidths of higher frequencies, while avoiding the severe propagation limits of mmWave and sub-THz. This balance of reach, penetration, and capacity makes FR3 the **most promising new band for 6G**, positioned to deliver scalable capacity on existing macro grids while extending into urban and enterprise deployments.

FR3 is not just another incremental layer: it represents the **primary new capacity range for 6G**, where wide-area macro coverage, enterprise networks, and emerging sensing functions converge. Unlike mmWave, which will remain a specialized augmentation, FR3 offers the right mix of physics and bandwidth to anchor mass-market 6G deployments worldwide.

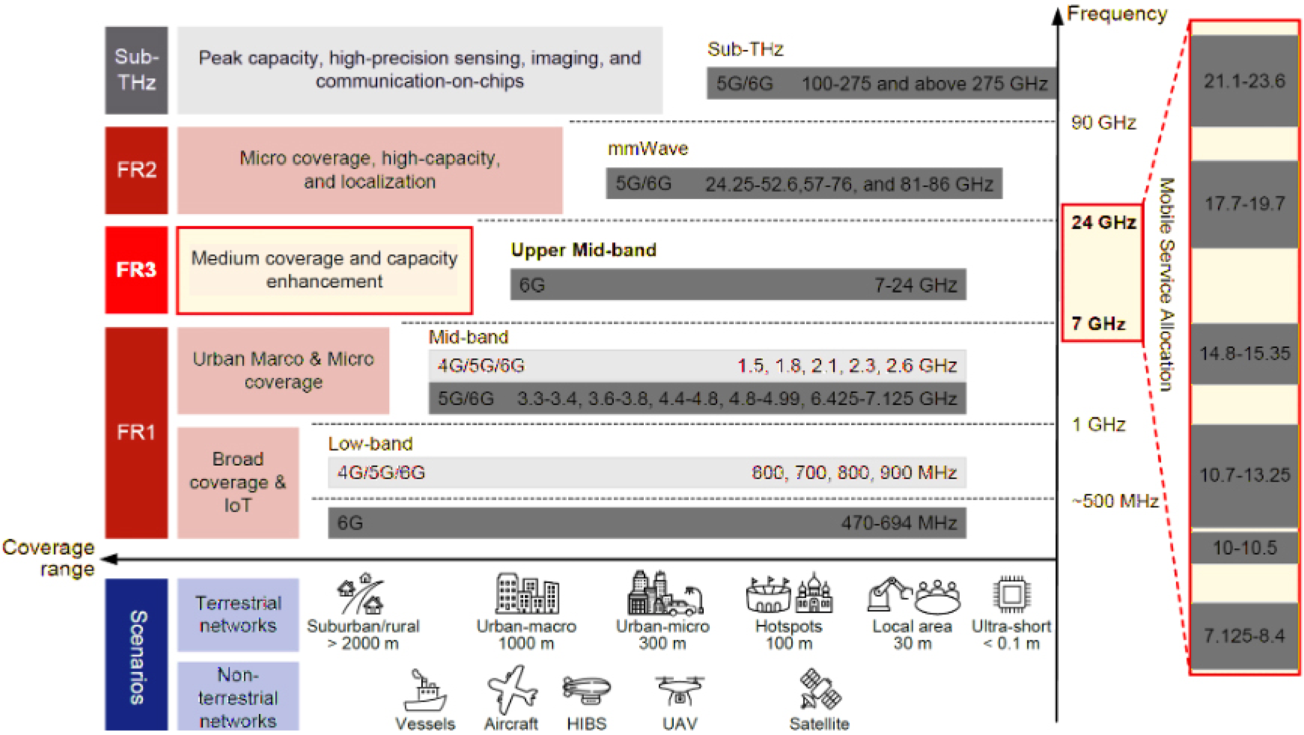
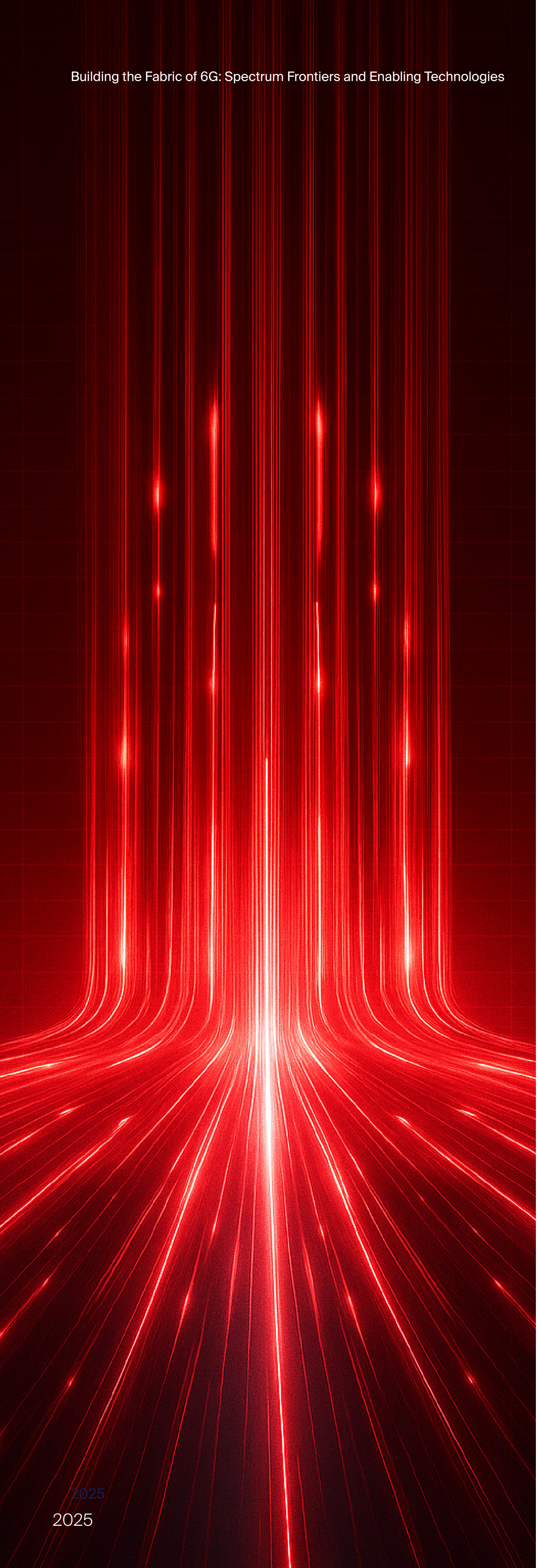


Figure 2: Spectrum overview of the mobile network [2]



4.1 Lower FR3 (7.125 - 8.5 GHz)

- **Coverage and Propagation**

At the entry point of FR3, propagation still resembles C-band performance. Signals in the 7–8.5 GHz range can travel hundreds of meters and penetrate walls with only slightly more loss than 3.5 GHz. This makes the band attractive for macro deployments, where it can extend capacity without requiring radical changes in site density.

- **Capacity and Performance**

The appeal of this sub-range lies in the **broad new spectrum blocks under study for WRC-27.** With channels as wide as 400 MHz, networks could deliver multi-gigabit user experiences comparable to mmWave, but with far greater reach. When paired with **XL-MIMO panels (Extremely Large-Scale MIMO),** each site could support tens of gigabits of capacity, enough to serve crowded city centers and suburban clusters.

- **Deployment Outlook**

Lower FR3 is expected to be the **entry point for most operators and regulators.** It builds naturally on existing 5G macro grids, making deployment straightforward. The main obstacle lies in **incumbent radar and satellite systems,** particularly military radars around 8 GHz, which will require advanced sharing frameworks such as beam nulling and automated coordination.

4.2 Mid FR3 (10-15 GHz)

- **Coverage and Propagation**

In the 10–15 GHz range, propagation begins to lean toward line-of-sight dominance. Diffraction weakens, and walls impose an additional ~10 dB penetration loss compared to lower FR3. Nevertheless, multipath remains sufficiently rich to sustain non-line-of-sight coverage, especially with the help of small supplementary nodes indoors.

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- **Capacity and Performance**

The mid-FR3 spectrum offers **contiguous 500–1000 MHz blocks**, supporting user peak rates of 10–20 Gbps. Multipath scattering enables 8–16 spatial layers, allowing networks to serve many simultaneous users with consistent reliability. Compared to mmWave, mid-FR3 strikes a balance, providing substantial capacity without the severe coverage limitations of higher frequencies.

- **Deployment Outlook**

This sub-range is particularly attractive for **urban and suburban capacity upgrades** and for **enterprise networks.** Indoors, it can deliver factory- or campus-wide multi-gigabit service with fewer nodes than mmWave, making it cost-effective for industrial and commercial deployments. However, incumbent satellite uplinks between 12–14 GHz pose challenges for global harmonization, likely resulting in regional variations in spectrum availability.

4.3 Upper FR3 (15-24 GHz)

- **Coverage and Propagation**

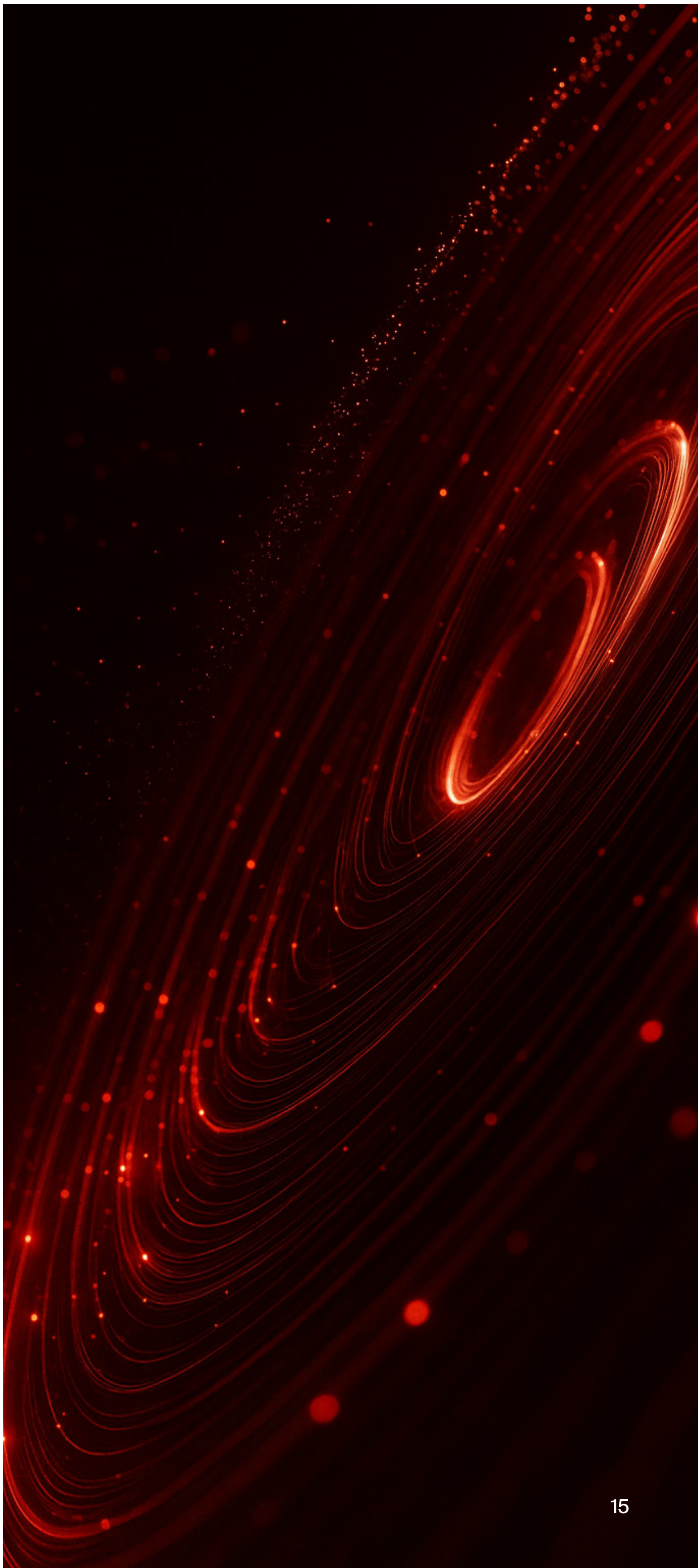
At the upper end of FR3, propagation characteristics approach those of mmWave. Coverage radii shrink to 100–300 meters in dense cities, and penetration losses make indoor service more difficult. This sub-range is therefore best suited to small-cell deployments and hotspot capacity.

- **Capacity and Performance**

The payoff is enormous bandwidth. With **1–2 GHz channels**, networks could deliver 20 Gbps per user under ideal conditions. However, performance depends heavily on efficient **MU-MIMO (Multi-User MIMO**) operation and mitigation of blockages.

- **Deployment Outlook**

Upper FR3 will find its home in **dense urban grids, enterprise venues, and indoor hotspots** where extreme capacity is needed. It also serves as a **transition zone into mmWave**, offering higher throughput than mid-FR3 while maintaining slightly better coverage than FR2.



4.4 Enabling Technologies

The hybrid regime of FR3, where users may lie in the far field (FF) at one sub-band but in the near field (NF) at another, creates unique challenges for beam management, and transceiver design. Addressing these challenges calls for regime-aware, frequency-adaptive, and spatially flexible solutions that can dynamically adjust to user conditions.

One of the most critical enablers is regime-aware hybrid beamforming. Unlike fixed analog or static digital precoders, regime-aware designs adapt subarray activation and phase alignment depending on whether a user is in the NF or FF at a given frequency. Delay curvature, Doppler divergence, and polarization drift across large apertures provide valuable signatures that can be exploited to classify user regimes and reconfigure beams accordingly. This allows the system to avoid misalignment, maintain array gain, and deliver more consistent throughput across sub-bands, particularly at the higher end of FR3 where near-field effects dominate.

Another transformative technology is the use of **Reconfigurable Intelligent Surfaces (RIS).** Traditionally envisioned as passive reflectors to extend mmWave signal coverage, in FR3 they can take on more dynamic and intelligent roles. RIS panels can act as signal profilers, assisting with regime detection by observing multipath features that may differ from those seen at the base station. They can also operate as regime-aware redirectors: generating spherical-like wavefronts for NF users and planar ones for FF users, thus improving beam alignment, filling coverage gaps, and enabling robust service continuity in cluttered urban environments.

FR3 motivates advanced control and intelligence in beam management. Its frequency-selective spatial non-stationarity, visibility region fragmentation, and sub-band-dependent multipath demand real-time adaptation. **Adaptive beamforming and AI-driven beam tracking** will be essential in such dynamic environments. Rather than simply react to blockages, machine learning algorithms will predict interruptions and pre-emptively redirect connections, ensuring seamless mobility and resilience. AI-based methods — from reinforcement learning to spatio-temporal neural models — will be applied to anticipate regime transitions, beam directions, and Doppler variations, enabling proactive calibration and faster tracking. In this sense, FR3 becomes a proving ground for AI-native RANs, where algorithms orchestrate beams, spectrum, and resources in real time.

Together, these empowering technologies — hybrid beamforming, RIS-assisted diversity, and AI-driven beam control — form the foundation of a regime-aware and frequency-adaptive architecture that can fully realize FR3's promise as the workhorse band of 6G.

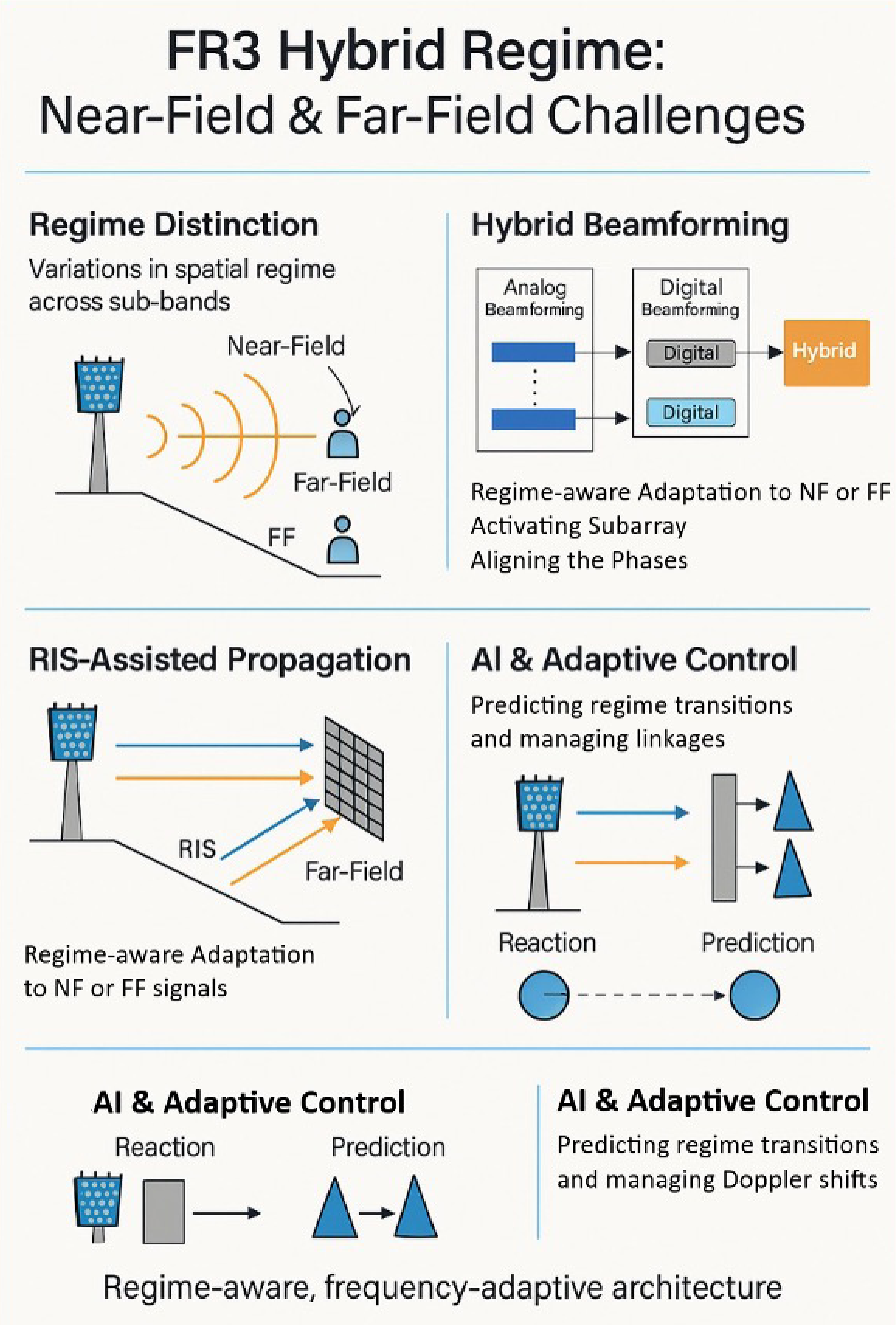


Figure 3: 6G Enabling Technologies

4.5 Regulatory Considerations

The FR3 spectrum is densely populated with incumbent services. Civilian and governmental users — from satellite systems and radar to meteorology and radio astronomy — occupy much of this range, making relocation difficult. This makes international coordination essential.

At **WRC-23**, discussions on FR3 were limited, but **WRC-27** is expected to play a pivotal role, with candidate ranges including **4.400-4.800 GHz,** or parts thereof, in Region 1 and Region 3.

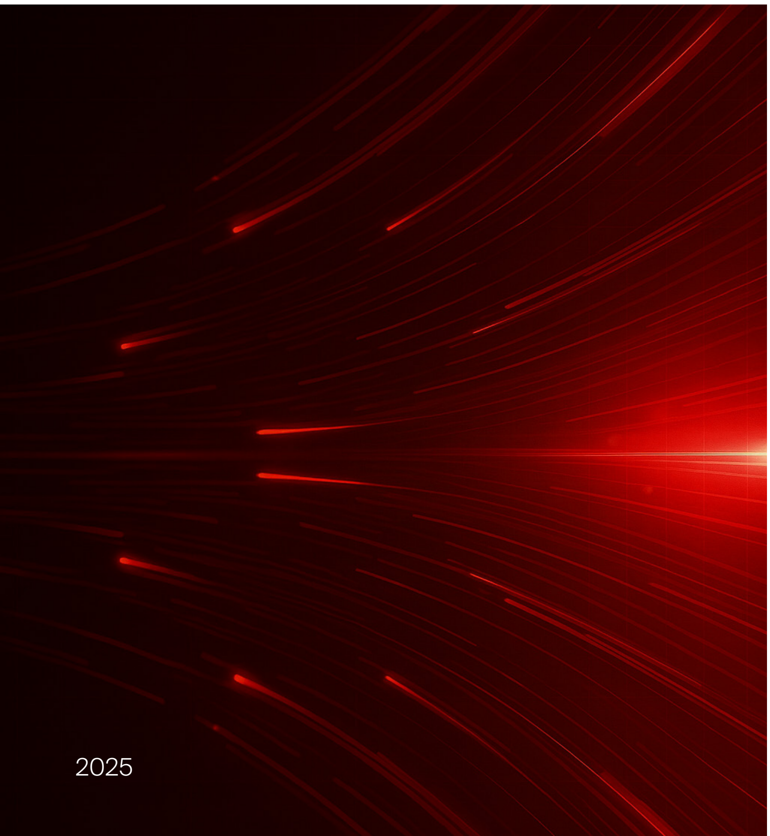
7.125-8.400 GHz, or parts thereof, in Region 2 and Region 3.

7.125-7.250 GHz and 7.750-8.400 GHz, or parts thereof, in Region 1.

14.8-15.35 GHz, in Region1, 2 & 3.

Already, the U.S. FCC has moved to repurpose the 12.7–13.25 GHz band for 6G, while the UAE's **TDRA** has expressed strong interest in early FR3 trials, building on its pioneering 6 GHz adoption.

Global harmonization will determine whether FR3 can achieve its potential as the unifying capacity layer for 6G. Fragmentation would slow ecosystem development and raise costs, while alignment could enable a **globally scalable device and infrastructure market.**



4.6 Strategic Role

FR3 is poised to become the primary new spectrum layer of 6G deployments, filling the gap between FR1's wide-area reliability and mmWave's extreme capacity. Its segmentation highlights its versatility:

- **Lower FR3 (7–8.5 GHz)** will expand macro coverage.
- **Mid-FR3 (10–15 GHz)** will deliver urban and enterprise capacity.
- **Upper FR3 (15–24 GHz)** will serve dense hotspots and act as a bridge into mmWave.

Beyond broadband, FR3 will enable **new forms of intelligence across industries.** By harnessing technologies such as RIS and ISAC, enterprises will be able to deploy **private 6G networks** that combine high-throughput connectivity with **environmental sensing and context awareness.** This dual capability will open opportunities in **smart cities, autonomous mobility, industrial automation, and logistics,** where the network must not only connect but also sense and adapt to its environment.

Strategically, FR3 must also be deployed with **sustainability in mind**. Dense deployments could otherwise raise energy costs, but AI-driven sleep scheduling, efficient XL-MIMO, and RIS-assisted coverage will reduce power consumption per bit. At the same time, **security** will be critical: narrow beams provide some confidentiality, but resilience against jamming, spoofing, and handover attacks will require robust encryption, AI-based anomaly detection, and quantum-safe cryptography.

For countries like the UAE, FR3 represents an opportunity to take global leadership. Building on the early allocation of 6 GHz and pioneering trials, the UAE's proactive posture positions it to be among the first adopters of FR3, setting the stage for national 6G rollouts by 2030.

e& UAE is pursuing a forward-looking and multi-layered spectrum strategy to enable its 6G ambitions.

Key elements include :

- **Spectrum expansion & testing:** The operator has already begun trials of newly allocated bands (such as 6 GHz and 600 MHz) under TDRA's spectrum plan, achieving ultra-high data rates (≈ 10 Gbps) in 6 GHz combined with existing FR1 bands, and extended coverage with 600 MHz.

- **Regulatory alignment & roadmap:** e& UAE works closely with TDRA's 6G Roadmap, which includes establishing committees and standards work (with partners like Khalifa University, global standards bodies) plus regulatory sandboxing to test and refine spectrum usage ahead of commercial deployment.

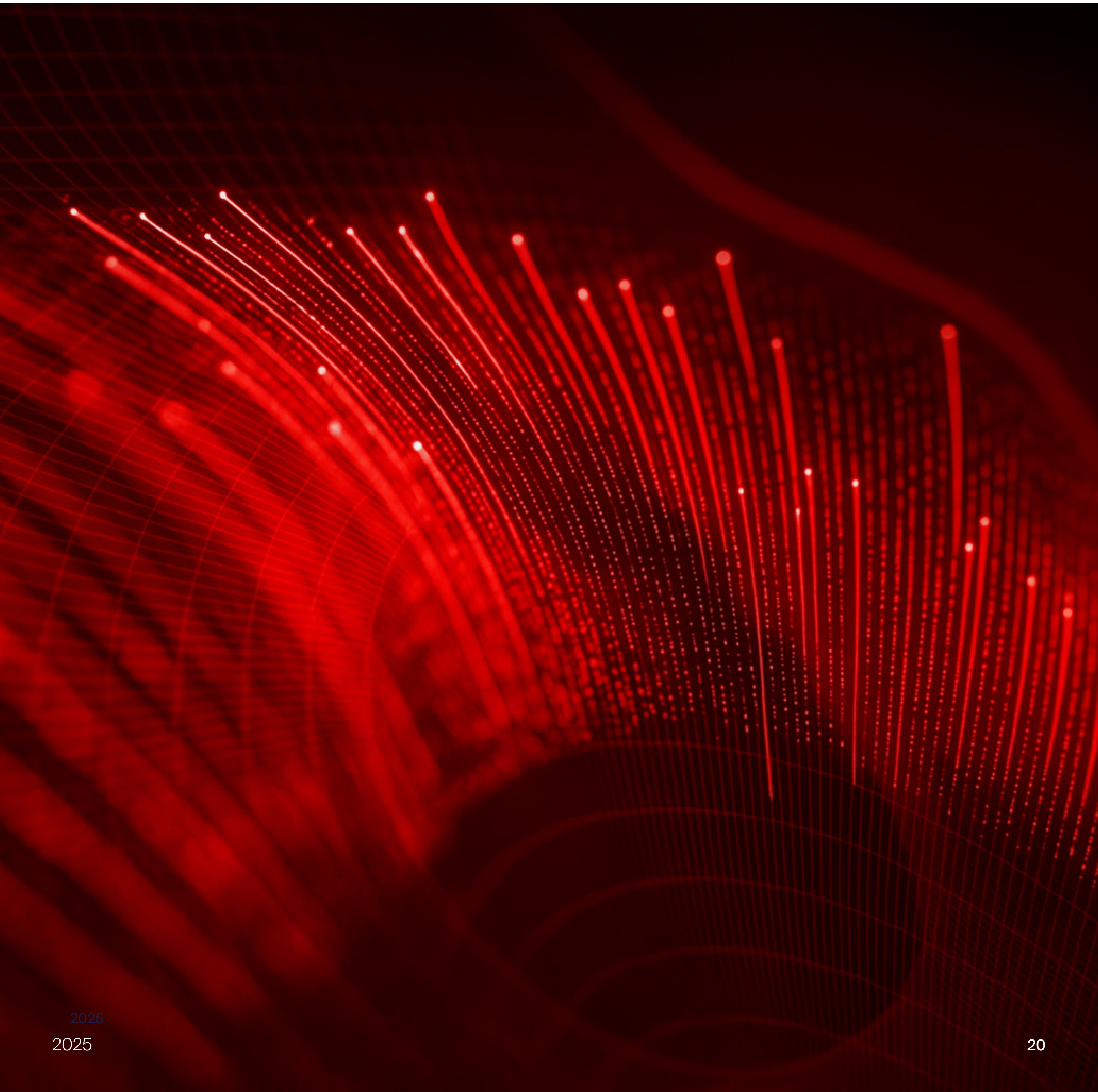
- **Focus on new spectrum bands:** The strategy emphasises acquiring and using spectrum in higher frequency ranges (e.g. upper 6 GHz, sub-THz as it matures) to support high-throughput and low-latency services, while also using low and mid bands (like 600 MHz, FR1) to ensure wide coverage and indoor penetration.

- **Technology enablers:** Alongside spectrum, e& UAE is investing in technologies that make spectrum more efficient and usable, including AI-native networks, integrated sensing and communications (ISAC), reconfigurable intelligent surfaces (RIS), and non-terrestrial networks (NTNs). These enable richer use cases, tighter integration of network and environment, smarter allocations, and better coverage, especially in challenging settings.

- **Timeline and phased deployment:** The strategy implies a phased timeline—early research, standards, and technical trials in the mid-2020s; early commercial applications in selected zones; then broader deployment by around 2030 or slightly beyond.

5. Spectrum Between 24–100 GHz (mmWave): Extending and Enhancing High-Band Coverage

When 5G first stepped beyond 6 GHz, it was the **millimeter-wave (mmWave) spectrum** that captured global attention. Operating between 24 and 100 GHz, mmWave offered multi-gigabit speeds and vast bandwidths, but also revealed the limits of physics: fragile propagation, sensitivity to blockage, and the need for dense site deployments. In 6G, mmWave will no longer be the headline band, but it will remain a **vital complement**, extending capacity in dense hotspots, supporting specialized enterprise deployments, and bridging the spectrum roadmap toward sub-THz.



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5.1 Coverage and Propagation

At mmWave frequencies, propagation is a story of extremes. Signals deliver unprecedented capacity but struggle to travel far. In open outdoor environments, ranges extend only a few hundred meters, and in dense urban grids, coverage can shrink to 100 meters or less. Walls, foliage, and even human bodies can attenuate mmWave signals by tens of decibels, making them highly dependent on **line-of-sight (LOS) paths.**

Between 24–40 GHz **(the lower mmWave range)**, propagation remains challenging but manageable with careful deployment, allowing both outdoor and some indoor penetration. At higher ranges (40–100 GHz, the upper mmWave tier), attenuation increases sharply, reflections scatter unpredictably, and diffraction becomes negligible. Coverage becomes truly localized — but so too does the capacity potential.

5.2 Capacity and Performance

The strength of mmWave lies in its **massive contiguous bandwidths.** Channels of 400 MHz to 1 GHz, and in some cases multiple GHz of spectrum, are available for IMT. With such wide channels, peak rates can exceed **20 Gbps per user,** and cell capacities can scale to hundreds of gigabits per second.

Latency is equally impressive. Short symbol durations and wide bandwidths allow near-real-time responsiveness, which is critical for immersive applications such as XR and holographic communication. However, this performance is confined to coverage zones where signals can be maintained — mmWave is a **layer of abundance in scarcity**, offering extreme capacity only where it can be reliably delivered.

5.3 Use Cases & Applications

In 6G, mmWave will find its niche in **dense urban environments**, **transport hubs, and enterprise venues.** Stadiums, airports, convention centers, and shopping malls will rely on mmWave to deliver multi-gigabit connectivity to tens of thousands of users simultaneously. Enterprises will leverage localized mmWave cells for private networks requiring secure, ultra-high-capacity service, such as AR-guided assembly lines or industrial digital twins.

Another key role will be in **fixed wireless access (FWA).** Where fiber deployment is impractical, mmWave links can provide last-mile gigabit service to homes and businesses. In 6G, improved beam management and advanced RF front-ends will enhance FWA reliability, making it a cost-effective alternative in both urban and rural edge zones.

5.4 Deployment Outlook

The mmWave experience in 5G offers lessons for 6G. Initial deployments revealed that while mmWave delivers spectacular peak speeds, scaling coverage is costly and complex. As a result, in 6G, mmWave will not serve as the primary coverage band but as a **targeted augmentation layer**, complementing FR1 and FR3.

Operators are expected to integrate mmWave more seamlessly into **multi-layer spectrum orchestration**, with AI-based resource management ensuring users are handed over to mmWave cells only when beneficial. In enterprise contexts, mmWave will be deployed as **localized private networks**, covering factories, campuses, or event venues with extreme capacity where needed.

In the UAE and other leading markets, mmWave is already being tested for **specialized use cases such as FWA and smart venue coverage,** providing a foundation for its evolution into 6G-era deployments.

5.5 Enabling Technologies

Several innovations will be critical to overcoming mmWave's limitations in 6G:

- **Beamforming and Beam Tracking:** Highly directional beams must be maintained with centimeter-level precision. AI-assisted tracking will predict user movement and proactively adjust beams to avoid drops.
- **Multi-Connectivity:** Devices will rely on dual connectivity, using FR1 or FR3 for control and fallback while opportunistically connecting to mmWave for capacity bursts.
- **RIS for Coverage Extension:** Reconfigurable intelligent surfaces will redirect beams into shadowed areas, improving coverage in urban canyons or indoor spaces.
- **AI-Native Resource Orchestration:** AI will dynamically decide when to activate mmWave links, optimizing energy use while ensuring seamless user experience.

Together, these technologies will transform mmWave from a fragile standalone solution into a **reliable high-capacity complement** to FR1 and FR3.

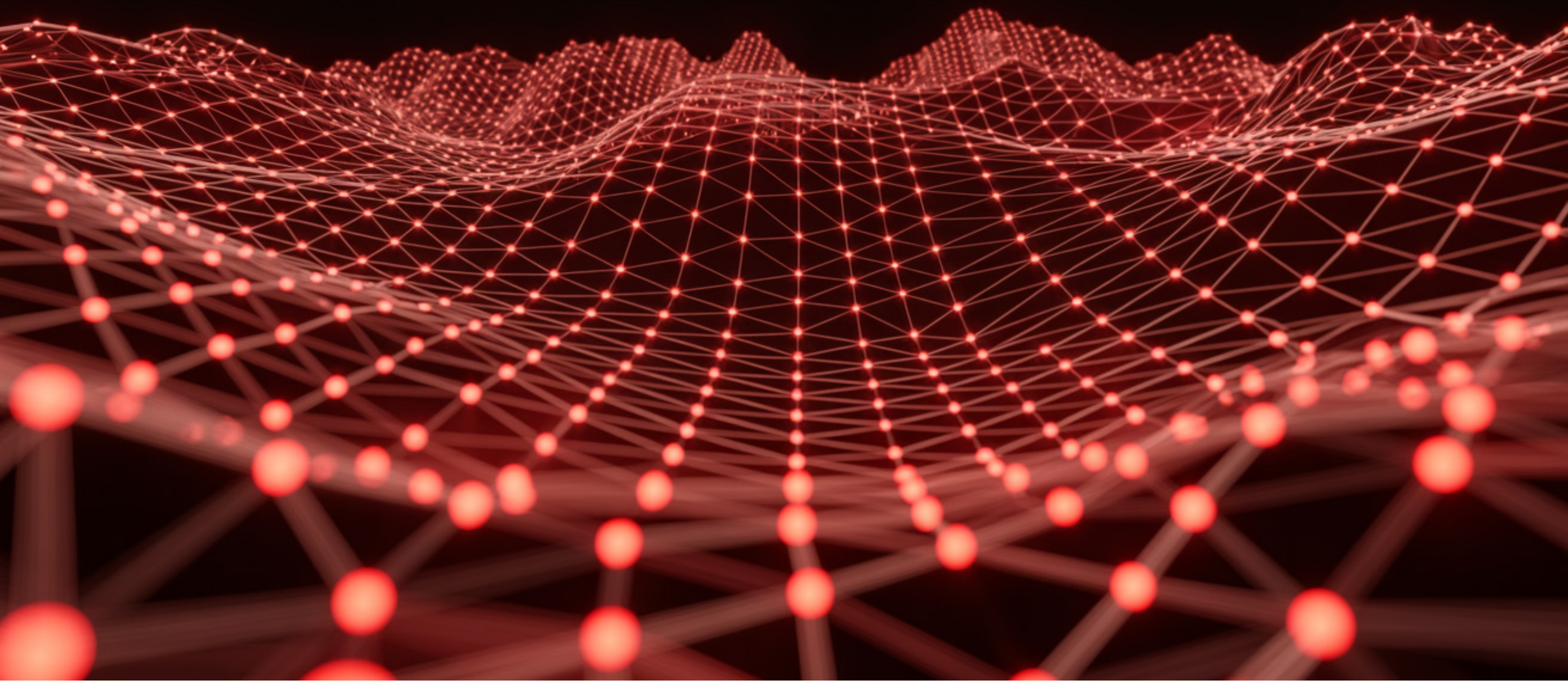
5.6 Strategic Role

In the broader 6G spectrum strategy, mmWave will serve as an **augmenting layer** rather than the foundation. Its role will be to extend and densify networks in areas where capacity demand peaks, enabling immersive services for large crowds, enterprise verticals, and FWA.

From a **sustainability perspective**, mmWave must be used intelligently. Dense deployments risk raising energy consumption, but AI-driven on-demand activation and RIS-assisted coverage will reduce unnecessary power use. From a **security perspective**, mmWave beams are naturally directional, which enhances confidentiality, but networks must still guard against jamming and beam hijacking, particularly in private deployments.

Ultimately, mmWave will remain a **bridge technology** in the spectrum roadmap. It demonstrates the feasibility of multi-gigabit wireless, extends 5G learnings into 6G, and paves the way for sub-THz exploration. While it may not dominate 6G the way it was once envisioned for 5G, mmWave will be indispensable as the **high-band complement** in the multi-layer fabric of 6G networks.

e& UAE has progressed significantly in deploying mmWave (FR2) technologies to enable ultra-high capacity and enterprise-grade connectivity. A major milestone was achieved with a pilot deployment over the 26 GHz band covering upto 11km with LOS beams towards high power CPEs and enabler for FWA that reside far away from the mobile sites, delivering high throughput suited for fixed wireless access and private network applications. The operator also completed a private 5G Proof-of-Concept with ZTE that demonstrated multi-band capability (mmWave, mid-band, low-band) and achieved uplink speeds up to 2.04 Gbps, showcasing how mmWave can be effectively combined with edge computing to support latency-sensitive enterprise use cases and faster, more flexible network deployment.



6. Spectrum Beyond 100 GHz: Sub-THz and THz Frontier

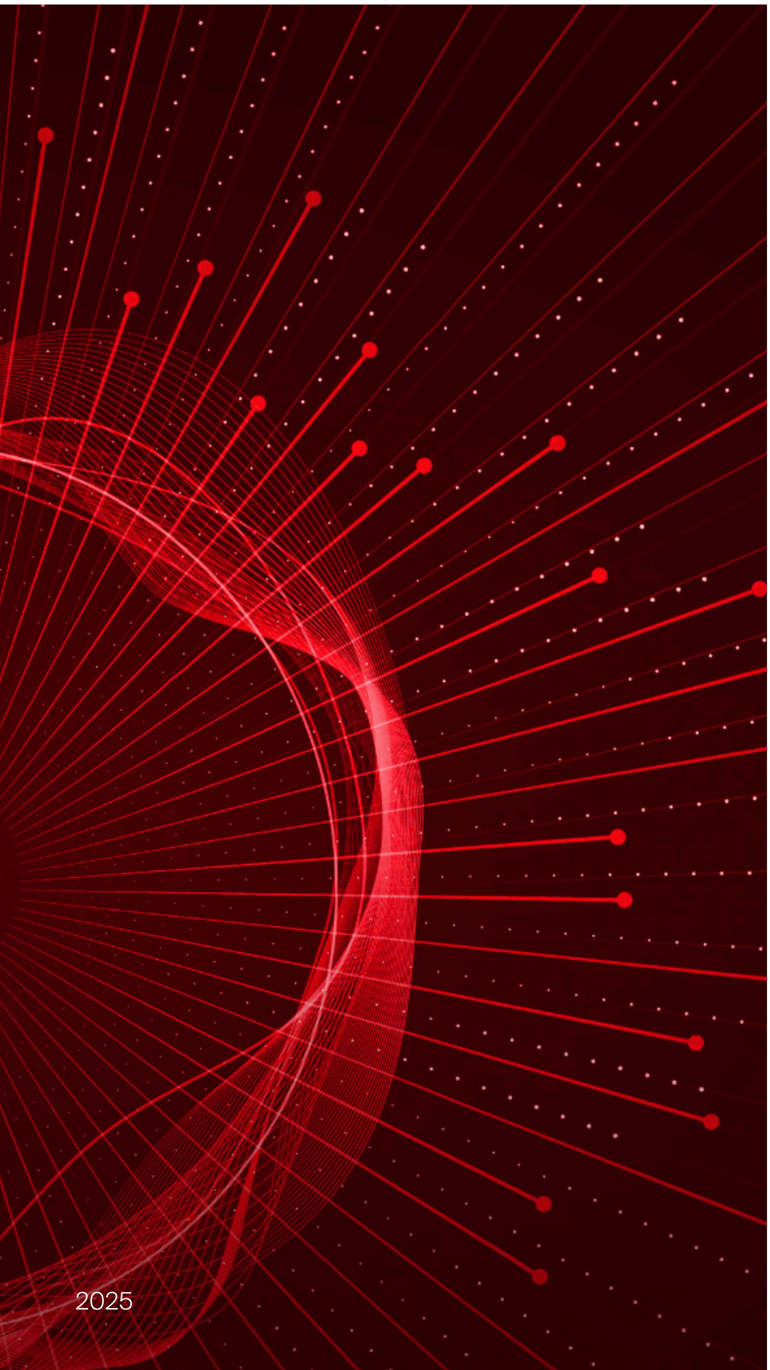
Beyond 100 GHz lies the boldest frontier of 6G: the **sub-Terahertz (100–300 GHz) and Terahertz (0.3–1 THz) bands.** These frequencies promise extraordinary capabilities — terabit-class links, radar-like sensing, and sub-millisecond latency — but demand a rethinking of how radios are built and deployed. Here, physics is unforgiving: signals fade within tens of meters, absorption peaks carve gaps in the spectrum, and walls or even glass can halt propagation. Yet within these limitations lies the potential to unlock the most transformative applications of 6G.

6.1 Coverage and Propagation

Propagation beyond 100 GHz is shaped by uncompromising physics. Free-space path loss scales sharply with frequency according to the Friis equation, while molecular absorption from oxygen and water vapor carves deep notches into the usable spectrum. These effects create spectral “windows” of relatively low absorption that can be exploited for communications, separated by bands where transmission is severely attenuated. As a result, a signal at 140 GHz or 300 GHz may travel only tens of meters before fading into noise.

Penetration is also poor: walls, foliage, and even glass can block THz signals almost entirely, making outdoor deployment feasible only over very short ranges, often line-of-sight. Unlike lower bands, surface interactions at THz wavelengths (sub-millimeter scale) are heavily influenced by material roughness, producing diffuse scattering and randomization that classical ray-based models cannot accurately capture. This necessitates new deterministic and statistical channel models.

Yet these limits also create unique opportunities. The extreme directivity of THz beams minimizes interference and enables highly efficient spatial reuse, allowing multiple links to operate side-by-side with negligible crosstalk. Reflections behave more like specular mirrors than scatterers, allowing precise and predictable beam steering but eliminating the rich multipath that lower bands exploit. Outdoor THz environments tend to exhibit sparse multipath dominated by line-of-sight (LOS), though non-line-of-sight (NLOS) components may still appear in short-range, indoor, and industrial scenarios. THz coverage will therefore be limited and surgical—but within those zones, it can achieve unprecedented precision and reliability.



6.2 Capacity and Performance

What THz loses in reach, it compensates with raw throughput and precision. A single allocation may provide **10–20 GHz of contiguous bandwidth**, dwarfing what is possible in FR1, FR3, or even mmWave. With such resources, 6G links can scale into the **hundreds of gigabits or even terabit-per-second class**, enabling ultra-high-capacity connections. At these frequencies, symbol durations shrink to the picosecond scale, supporting sub-millisecond latencies and precise synchronization critical for holographic communications, extended reality, and industrial digital twins.

The extremely small wavelengths allow extra-large antenna arrays (XL-MIMO) to be packed into compact apertures. Unlike today's far-field MIMO systems, many users in THz bands fall within the near field, where the Fresnel region extends outward because the boundary scales with aperture size squared over wavelength. This requires spherical-wave channel models and near-field beamforming, transforming arrays into lenses that can focus energy not only by angle but also by distance. Such capabilities unlock spatial multiplexing on an unprecedented scale, turning antenna arrays into **joint communication-and-sensing platforms.**

Importantly, because absorption increases with distance, the usable bandwidth shrinks as links extend, meaning adaptation must be distance- and frequency-aware. This tradeoff—limited reach but extreme performance—defines the THz frontier: a band where carefully engineered short-range deployments will enable 6G's most demanding applications.

6.3 Enabling Technologies

Historically, the THz band was referred to as the “THz gap” due to the absence of efficient devices.

Recent breakthroughs in semiconductor technologies, however, have enabled the development of reliable sources, detectors, and integrated components capable of operating at THz frequencies. This technological maturation now positions the THz band as a promising frontier for 6G networks.

THz waves lie in the portion of the frequency spectrum between the realms of light waves and radio waves, enabling two primary methods for generation and detection: **electronics-based and photonics-based** approaches.

- In the **electronics-based approach**, a lower-frequency oscillator is upconverted through amplifier and frequency-multiplier chains, while reception uses a similar downconversion process to intermediate or baseband frequencies, followed by digital signal processing. This pathway supports compact integration and large phased arrays but suffers from low output power, amplifier inefficiency, and limited-resolution phase shifters.

- In the **photonics-based approach**, two optical sources (lasers) are combined in a photomixer to generate a THz signal at their frequency difference. Receivers employ dual-laser configurations with RF mixing to recover the baseband. Photonics-based systems deliver wide tunability, high spectral purity, and frequency-independent steering via optical true-time-delay lines, eliminating beam squint—a limitation in electronic designs.

- **Hybrid systems** increasingly combine both methods, with photonics providing high-quality THz generation at the transmitter and electronics offering compact, efficient detection at the receiver.

These front-end implementations directly shape the **PHY layer design space**. At THz frequencies, beamforming is no longer optional but essential: severe free-space path loss and molecular absorption demand highly directional transmissions to sustain link budgets. Unlike lower bands, where omnidirectional or wide beams are viable, THz relies on narrow beams for high antenna gain, precise spatial focusing, and robustness against interference.

The extremely short wavelengths allow **extra-large arrays (XL-MIMO)**—with hundreds or thousands of elements—to be compactly integrated. This enables multi-beam operation, spatial multiplexing, and agile beam tracking. Importantly, the **near-field region** expands at these frequencies, placing many users within the Fresnel zone. This shifts beamforming from conventional planar-wave to **spherical-wave models**, requiring energy to be focused in both angle and distance. Such near-field beamforming allows sharper spatial separation of users but demands complex channel estimation and adaptive beam management.

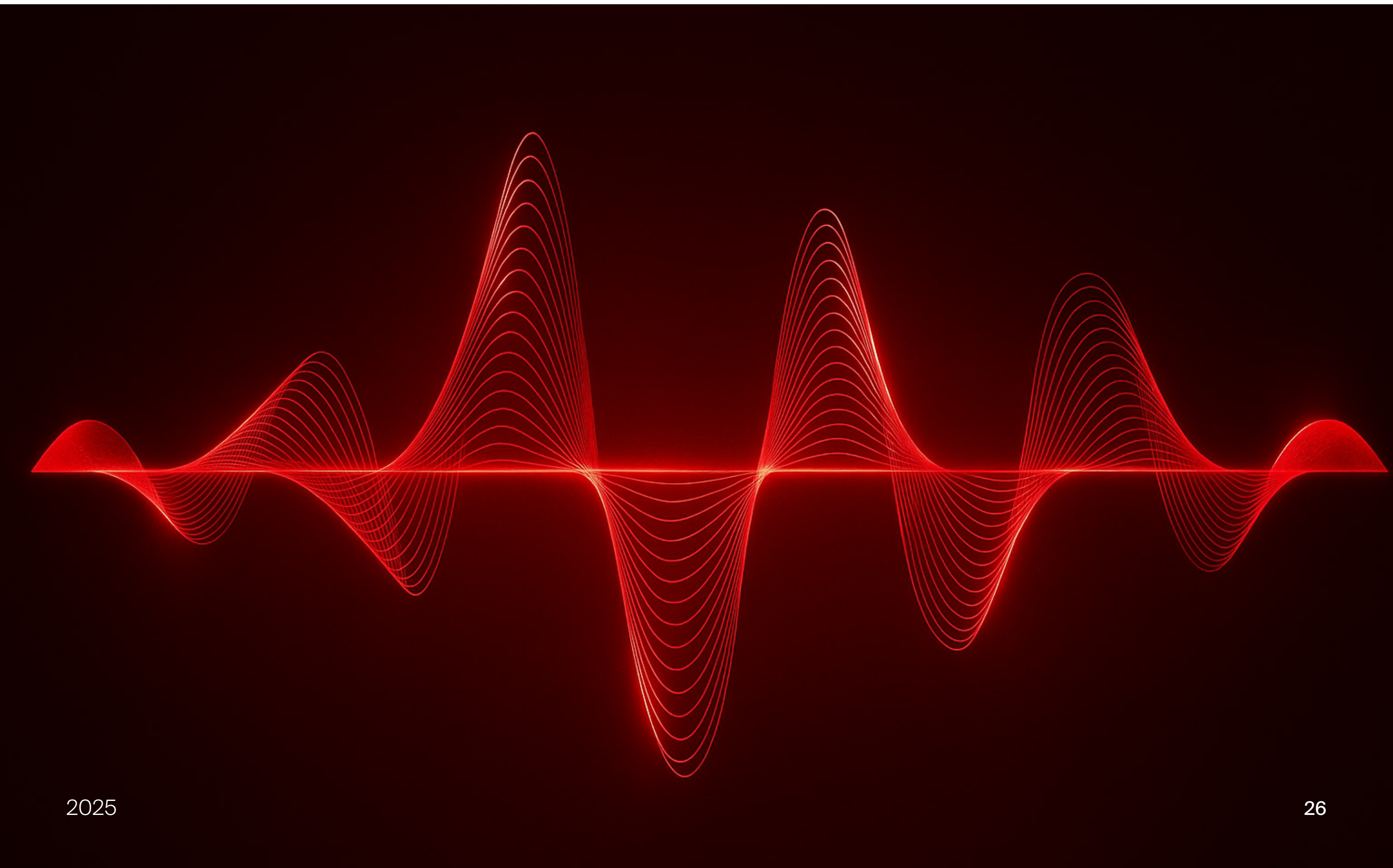
Photonics-based beamforming further extends these capabilities by leveraging true-time-delay lines for precise, frequency-independent beam control across wide bandwidths. This makes them particularly promising for **holographic, sensing, and imaging applications** where angular and range-domain focusing are equally critical.

Beyond beamforming, **Reconfigurable Intelligent Surfaces (RIS)** offer a complementary approach for managing fragile THz beams. By redirecting or bending signals indoors, RIS can create virtual line-of-sight paths in otherwise obstructed environments, extending coverage and improving link reliability.

Another critical enabler is **distance- and frequency-aware link adaptation.** Unlike lower-frequency channels, THz propagation varies drastically across spectrum and distance. Attenuation increases sharply with range, while absorption produces spectral “windows” of relatively low loss. Consequently, modulation, coding, and bandwidth allocation must adapt dynamically based on both distance and frequency. Higher-order modulation and wide bandwidths are sustainable at short range in low-absorption windows, while longer links require narrower beams and lower-order modulation. Experimental work, such as measurements carried out using the custom-design atmospheric chamber at the NYUAD Wireless Center, has already validated adaptive strategies across sub-bands including **120–140 GHz, 140–160 GHz, 220–240 GHz, and 275–325 GHz.**

Finally, practical deployment must address **thermal and energy challenges.** THz hardware is inherently power-hungry and heat-limited, necessitating advances in cooling, miniaturization, and energy-aware design. AI-optimized transmission strategies will play a key role in sustaining performance while ensuring system efficiency.

Most significantly, sub-THz and THz are poised to become the **true home of Integrated Sensing and Communication (ISAC).** Unlike FR3, where sensing is supplementary, at THz frequencies communication and radar-like sensing merge seamlessly. This convergence enables centimeter- to millimeter-level accuracy in localization, imaging, and environment perception—turning 6G networks into intelligent, environment-aware fabrics that can support applications ranging from autonomous vehicles to smart factories.



6.4 Use Cases & Applications

The unique capabilities of sub-THz and THz frequencies position them as the foundation for the most demanding 6G services—scenarios where no other spectrum layer can deliver the required performance. Among the most striking examples is holographic telepresence, where human-realistic holograms with full 3D video and audio fidelity may demand on the order of 0.5 to 1 terabit per second per stream. This is bandwidth that only THz spectrum can support. Extended reality will also evolve far beyond today's gaming and visualization applications, transforming into persistent, multi-sensory environments with ultra-high resolution and wide fields of view. To ensure seamless rendering without latency-induced distortion, such immersive experiences will push wireless data rates into the hundreds of gigabits per second, making THz an indispensable enabler of next-generation communication.

Beyond raw throughput, THz bands unlock a new paradigm by natively combining communication with sensing. At these ultra-short wavelengths, centimeter- and even millimeter-level accuracy becomes possible, embedding radar-like perception directly into the network fabric. This integrated sensing and communication allows the same infrastructure to provide high-speed connectivity while simultaneously perceiving its environment. In industrial and urban contexts, this dual functionality supports large-scale digital twins—live, data-rich replicas of cities, factories, or even human bodies—where machines, infrastructure, and people can be monitored and modeled with unprecedented spatial precision. Such capabilities will be critical for smart factories, autonomous systems, and mission-critical urban services where awareness and connectivity must converge.

Industries will also benefit from the ability of THz links to merge sensing with connectivity in very practical ways. Millimeter-level resolution enables robotic assembly lines to align parts with exact precision, quality inspection systems to detect the smallest defects, and material characterization tools to identify structural properties in real time. These functions illustrate how THz can transform industrial automation from isolated processes into interconnected, intelligent systems.

At the same time, THz offers unique opportunities for ultra-short-range, ultra-capacity links. Inside data centers and high-performance computing clusters, chip-to-chip and board-level interconnects can move beyond the constraints of copper or even fiber, replaced by wireless THz connections delivering fiber-class throughput across microscopic distances. On a larger scale, point-to-point backhaul between small cells or routers can be achieved using THz links, providing terabit-class capacity in places where trenching or fiber deployment is impractical.

These are not mass-market applications. They are specialized, high-value deployments, justified precisely because of the unique properties of the THz frontier. From human-realistic holograms to live digital twins, from intelligent factories to wireless interconnects within supercomputers, THz will not seek ubiquity but instead serve as the precision layer of 6G—deployed surgically where extreme capacity, ultra-low latency, and environment-aware connectivity are required.

6.5 Deployment Outlook

THz deployments will begin surgically, in places where their unique advantages outweigh their costs:

- **Indoor hotspots** such as stadiums, airports, and convention centers, where dense infrastructure can support Tbps service
.
- **Industrial campuses** requiring real-time sensing and terabit connectivity for robotics and logistics.
- **Data centers**, where THz backplanes could replace fiber for ultra-dense server racks.
- **Short-range urban backhau**l, bridging small cells or linking rooftops where fiber trenching is impossible.

These deployments will rely on hybrid strategies. Fiber and FSO will provide the backbone, while THz fills the **last tens of meters** with unmatched capacity and sensing. Research labs and operators worldwide are already running **THz testbeds**, and in the UAE, national initiatives are preparing for early trials that will feed into global standardization at **WRC-31.**

6.6 Strategic Role

Sub-THz and THz will not serve as the wide-area coverage layer of 6G, but their **strategic importance is undeniable.** They represent the **precision layer of the network**, powering the most demanding services such as holography, extended reality, **industrial automation, and high-resolution imaging.** More than a connectivity enabler, the THz frontier showcases the **convergence of communications**, **sensing, and intelligence,** positioning it as the ultimate proving ground for what 6G can achieve.

The very properties that make THz unique also define its challenges. **High directivity** improves confidentiality and reduces interference, but the **fragility of links** exposes them to disruption. Ensuring resilience will require **AI-driven intrusion detection, quantum-resistant cryptography, and physical-layer security techniques** such as artificial-noise beamforming. From a sustainability perspective, THz radios are inherently **energy-hungry**, given the demands of front-end electronics and cooling. However, intelligent deployment of **reconfigurable intelligent surfaces (RIS), AI-optimized transmission strategies, energy-aware beamforming, and hybrid photonic/electronic hardware** can dramatically reduce the carbon footprint, helping balance performance with efficiency.

Beyond public networks, sub-THz and THz will be especially attractive for **specialized private deployments.** In environments such as **research labs, defense sites, hospitals, and advanced manufacturing facilities**, their combination of **extreme data rates and integrated sensing capabilities** can justify highly localized networks, tailored to mission-critical needs. These deployments will act as stepping stones, demonstrating the feasibility of THz systems before broader adoption.

On the **geopolitical stage**, leadership in THz research carries outsized weight. Nations that master the **design, standardization, and ecosystem development** of THz systems will define the competitive landscape of 6G. For the **UAE**, this represents both an opportunity and a responsibility. Investments in **THz testbeds, academic–industry partnerships,** and frontier research—such as the work already underway at **NYUAD Wireless Center**—signal an ambition not just to adopt but to pioneer. With the **TDRA expected to support early THz pilots by 2030**, the UAE is positioning itself as a **6G innovation hub**, capable of shaping standards while showcasing frontier spectrum use.

By the time 6G matures in the 2030s, **those who master the THz frontier will set the pace of innovation**—not just in telecom, but across industries where connectivity, intelligence, and sensing converge. For nations like the UAE, THz leadership offers a pathway to **global influence in the future of connectivity.**

6.7 Regulatory Considerations

On the regulatory front, once appropriate frequency windows are identified through these research efforts, international alignment and spectrum policy will be essential to ensure effective utilization and global harmonization. The International Telecommunication Union (ITU) and national regulators are beginning to study candidate windows, but harmonization is still at an early stage.

Given their limited range and susceptibility to blockage, THz deployments are expected to be highly localized, concentrated in indoor environments such as stadiums, concert halls, and factories, as well as dense public venues like transportation hubs and campuses. These deployments will complement FR3's wide-area coverage with hyper-local, ultra-high-capacity "islands" of connectivity. Network architectures will evolve accordingly, with cell-free and ultra-dense topologies envisioned to compensate for short-range limitations while maximizing spectral reuse.

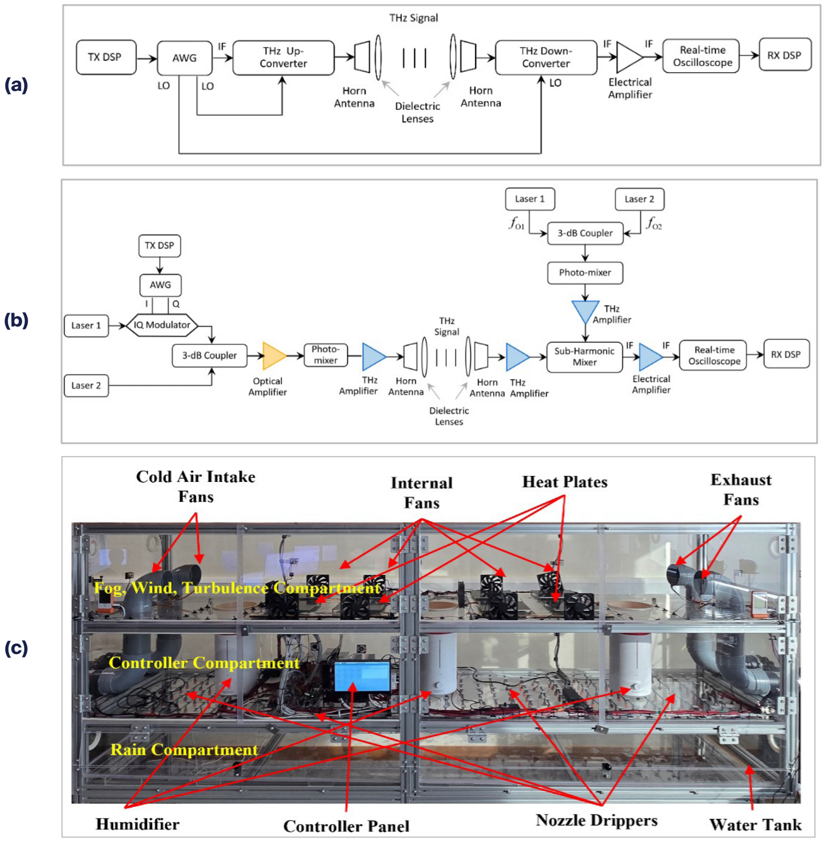
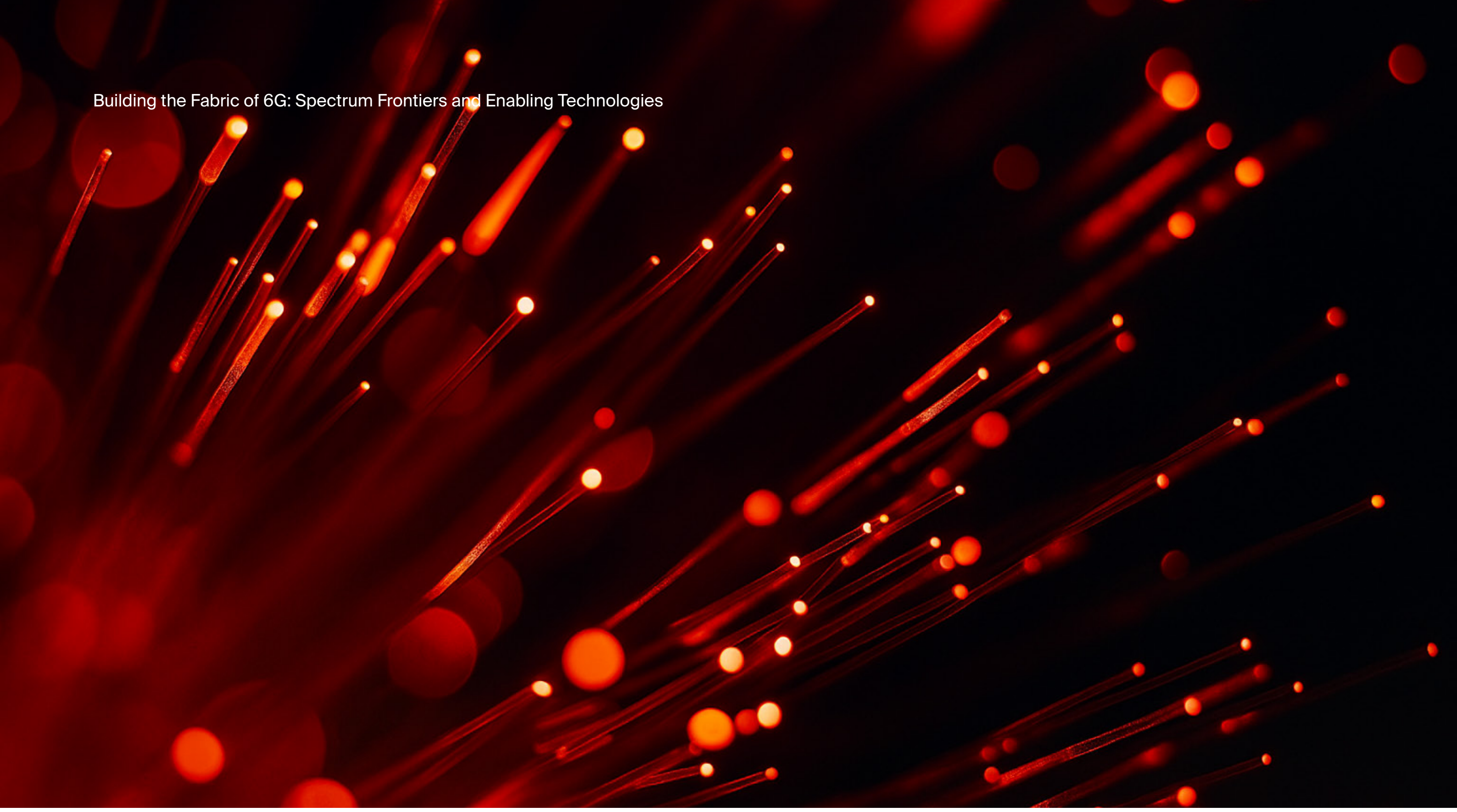


Figure 4: **(a)** Electronics-based THz testbed, **(b)** Photonics-based THz testbed , **(c)** Atmospheric chamber developed at NYUAD Wireless Center.

In a landmark collaboration, NYU Abu Dhabi Wireless Center and e& UAE are set to demonstrate the Middle East's first 6G Terahertz (THz) pilot, showcasing unprecedented data throughput of up to 145Gbps. This initiative represents not only a technical milestone but also a strategic leap, positioning the UAE at the forefront of global 6G innovation. The THz pilot will test ultra-high-capacity links that exceed the limits of current mmWave deployments, enabling terabit-class backhaul, holographic telepresence, and ultra-realistic extended reality applications. Beyond performance, the pilot symbolizes a new era of innovation for the Middle East, where academia, industry, and regulators converge to push the boundaries of connectivity. By pioneering THz trials ahead of WRC-31 spectrum studies, the UAE demonstrates its ability to shape international standards and ecosystems. This joint effort underscores the country's ambition to remain a global leader in technology innovation, driving forward the vision of intelligent, immersive, and sustainable 6G networks.



7. Backhaul for 6G: Fiber, RF, and Optical Wireless

As access networks expand into new spectrum bands and deliver unprecedented capacity, the **backhaul must evolve in lockstep.** Without a proportional leap in transport capability, the promise of **ultra-high-capacity mobility, immersive services, and terabit-class experiences** will remain constrained. In 6G, backhaul stops being a hidden enabler and becomes a **strategic pillar**: a multi-layer fabric blending fiber, RF, and optical wireless, orchestrated intelligently and designed to be resilient, scalable, and power-aware.

7.1 Fiber Backbone

Fiber remains the undisputed foundation of 6G transport. Its virtues are well known—**virtually unlimited bandwidth, extremely low latency, and high reliability**—which is why it anchors the core and metro and underpins dense urban small-cell clusters. Yet fiber is also **costly and slow to deploy** in rural or hard-to-dig environments, and it struggles to keep up in **fast-evolving** footprints where sites appear overnight.

In 6G, fiber itself becomes more **programmable and adaptive**. **SDN** brings intent-based control to optical layers**; AI-driven traffic engineering** dynamically reconfigures wavelengths and paths; and the **convergence of fixed and mobile transport** turns “fiber” into a **universal substrate** that carries fronthaul, midhaul, backhaul, and enterprise traffic as one coordinated plane.

7.2 Wireless RF Backhaul (mmWave & Sub-THz)

Where fiber cannot go quickly, **RF backhaul** fills the gap. The familiar microwave bands still matter, but the momentum shifts to **mmWave and sub-THz.**

- **E-band (71–86 GHz)** is already commercial at **10–40 Gbps** for 5G backhaul; with advanced modulation and tighter alignment, 6G links **scale toward ~100 Gbps** over short to medium distances.
- **Sub-THz (90–300 GHz)** opens **tens of gigahertz** of spectrum, enabling **100+ Gbps to Tbps-class** links for **short-range, dense deployments** in urban cores and hotspots.

RF backhaul is **faster to deploy** than fiber and **cost-effective** where trenching is impractical. The trade-offs are classic high-band realities: **alignment sensitivity, blockage, and weather**. That drives designs toward high-gain arrays, meticulous pointing, and in some sites **RIS-assisted relays** to bend around corners. Typical roles range from **urban small-cell mesh backhaul** and **rapid stands-up for events/ disaster recovery**, to **rural expansion** while fiber is on the way.

7.3 Optical Wireless Backhaul (FSO & LiFi)

Pushing further, **Free-Space Optics (FSO)** offers **fiber-like performance without trenches.** Once niche, FSO's reputation changed with spaceborne success—it now powers inter-satellite optical links at extreme rates. That heritage is moving to the ground: coherent detection boosts sensitivity and spectral efficiency, while adaptive optics stabilizes beams through turbulence. The result is terrestrial FSO that moves from **multi-hundred-Gbps toward the terabit scale,** ideal for **rooftop-to-rooftop** spans, river crossings, heritage districts, or rapid densification.

FSO is **license-free** and immune to RF interference, but **weather-sensitive—fog, dust, sandstorms** degrade links—and it demands **line-of-sight and precise alignment**. Indoors, **LiFi** adds a complementary option: short-range optical wireless links that can offload or **backhaul private/enterprise small cells** within campuses and buildings. In 6G, expect **FSO for urban rooftops and campus networks,** and a growing role in space–terrestrial integration (e.g., satellite gateways).

7.4 Deployment Models and Backhaul Considerations

Backhaul in 6G mirrors the **multi-layer spectrum strategy**—each access band suggests a preferred transport pattern:

- **Sub-7 GHz:** Nationwide macro coverage and control anchoring; **fiber or long-haul microwave** preferred for stability.
- **FR3 (7–24 GHz):** Macro and suburban capacity upgrades with moderate densification; **fiber where feasible,** or **E-band (71–86 GHz)** and **early sub-THz (90–140 GHz)** spans for reach and agility.
- **mmWave (24–100 GHz):** Urban hotspots, FWA, stadiums, enterprise venues; backhaul often via **IAB (Integrated Access & Backhaul), short-range E-band, or FSO rooftop** links.
- **Sub-THz/THz (>100 GHz):** Indoor giga-to-terabit zones, research campuses, specialized industrial clusters; **short-range sub-THz/FSO** backhaul, localized and complementary to fiber.

Across all layers, the pattern is **hybrid backhaul: fiber** as the primary anchor, complemented by **RF (E-band/sub-THz)** and **FSO** where speed, flexibility, or terrain demand it. **IAB** becomes a cost-control lever in dense mmWave/Sub-THz grids, letting small cells **serve users and forward** traffic on the same radio fabric.

7.5 Enabling Technologies

Three enablers tie this transport fabric together:

- **AI/ML backhaul orchestration** to forecast load, steer flows, and trigger **intelligent failover** across fiber/RF/optical paths—so SLAs hold when weather shifts or crowds move.
- **Multi-connectivity transport** that bonds **fiber + wireless** simultaneously for resilience and bandwidth elasticity.
- **Advanced antennas and relays—high-gain dishes, XL-MIMO** at sub-THz for stable pointing, and **RIS-assisted hops**—to tame alignment and extend reach.
- In dense grids, **IAB** reduces site costs and expedites rollout by reusing the access spectrum for backhaul hops.

7.6 Deployment Models and Orchestration

Backhaul in 6G is layered and adaptive:

- **Macro backhaul:** long-haul fiber and high-capacity RF trunks binding core ↔ regional hubs.
- **Metro backhaul:** dense fiber rings, **E-band** and early **D-band** meshes feeding city clusters.
- **Micro/enterprise backhaul:** **FSO** and short sub-THz spans delivering ultra-capacity into campuses, factories, venues, and tight small-cell grids.

An intelligent controller orchestrates these layers—placing flows, pre-empting failures, and optimizing end-to-end latency and cost. It understands weather, load, and maintenance windows; it knows when to light an FSO pair, when to swing to RF, and when to pin a route in fiber. The outcome is a transport plane that feels **elastic** to the RAN: always enough, always on, and always efficient.

The UAE has long been recognized as a global pioneer in fiber deployment, consistently ranking first worldwide in fiber-to-the-home (FTTH) penetration. This leadership—driven largely by e& UAE's early and aggressive investment in nationwide fiber infrastructure—provides a unique foundation for the 6G era. While many markets will need to rely on microwave or mmWave backhaul to fill transport gaps, the UAE's pervasive fiber grid ensures that future 6G sites can be seamlessly integrated into a high-capacity, low-latency backbone. By leveraging its unparalleled FTTH and metro fiber coverage, e& UAE can deliver on the vision of fiber-first backhauling, where fiber anchors every cell site, enabling ultra-reliable and sustainable transport for terabit-class 6G services. This approach not only guarantees the scalability needed for immersive applications like holography and extended reality, but also reduces dependency on less resilient alternatives, reinforcing the UAE's ambition to remain at the forefront of next-generation connectivity.

8. Global Spectrum Policy and Standardization Developments

Spectrum policy and international harmonization are as critical as technology in shaping the 6G future. Without global alignment, device ecosystems fragment, deployment costs rise, and services risk being regionally siloed. For 6G to succeed, regulators, standards bodies, and industry alliances must coordinate a **globally coherent spectrum roadmap** across low, mid, high, and frontier bands.

8.1 WRC Outcomes and Roadmap

WRC - 23:

- Identified **6425–7125 MHz (upper 6 GHz)** for IMT in many regions, marking the first major new global mobile allocation since C-band.
- Reaffirmed the **2 GHz** band and authorized **700–900 MHz**, **1.7–1.8 GHz**, and **2.6 GHz** bands as part of the **HAPS (High-Altitude Platform Stations)**, supporting non-terrestrial 6G integration.
- Opened discussions on potential UHF **(470–694 MHz)** repurposing in Region 1.

WRC-27 (expected focus):

- **7.125–8.5 GHz** as the first wave of FR3 IMT bands.
- **10–15 GHz candidates** under regional study, despite heavy satellite incumbents.
- Greater clarity on long-term **6G mid-band harmonization.**

WRC -31 (longer term):

- Anticipated to address **Sub-THz (100–300 GHz)** spectrum windows for IMT.
- Possible inclusion of **275–325 GHz** bands already being studied by ITU-R.

8.2 3GPP and ITU Role

- **3GPP:** Defining 6G as IMT-2030, standardization expected to begin with **Release 20 (2025–2026).** FR1/FR3 extensions will be prioritized before Sub-THz/THz.
- **ITU-R:** Leading global studies on spectrum coexistence, propagation models, and harmonization through its IMT-2030 framework.
- **Regional Regulators (FCC, CEPT, TDRA, etc.):** Driving early allocation decisions (e.g., FCC's 12.7–13.25 GHz proceeding, TDRA's swift adoption of 6 GHz).

8.3 Global Harmonization Imperative

- **Device Ecosystem:** Harmonized spectrum ensures chipsets and devices can be manufactured at scale. Fragmented allocations (e.g., different FR3 bands per region) would slow rollout and raise costs.
- **Roaming and Mobility:** Global consistency is essential for cross-border services and industries (aviation, maritime, logistics).
- **Verticals:** Enterprises and industrial users benefit from stable global bands for private 6G networks.

8.4 Emerging Trends in Policy

- **Dynamic Spectrum Sharing (DSS):** Regulators are considering AI-assisted spectrum access models where incumbents and IMT dynamically coexist.
- **Local Licensing:** More regulators (e.g., Germany, Japan) are opening mid-band spectrum for private **5G/6G networks.**
- **Satellite/Non-Terrestrial Integration:** Policies are evolving to allow **shared spectrum use** between terrestrial IMT and NTN (satellite, HAPS, UAV).
- **Green Spectrum Policy:** Increasing focus on **energy efficiency metrics** and spectrum sharing frameworks that minimize carbon footprint.

8.5 UAE- Specific Developments

The UAE's TDRA has been proactive in shaping global spectrum outcomes:

- Hosted **WRC-23** in Dubai, playing a pivotal role in aligning global agreement on the 6 GHz band.
- Among the **first regulators to allocate 6425–7125 MHz** for IMT.
- Allocated **600 MHz** for wide-area 5G/6G coverage.
- Expected to support early FR3 (7–8 GHz) trials and explore Sub-THz pilots in partnership with service providers such as e& UAE and local universities (e.g., NYUAD).

This positions the UAE as a **regional leader and early adopter,** influencing global policy while demonstrating national readiness.

In summary, global policy alignment is as critical as technical innovation in enabling 6G. WRC decisions, ITU studies, and regional regulator leadership will define the availability and usability of spectrum across layers:

- **WRC-23:** Delivered upper 6 GHz for IMT.
- **WRC-27:** Expected to crystallize FR3 allocations.
- **WRC-31:** Likely to open Sub-THz for IMT.

A harmonized spectrum roadmap will ensure that 6G achieves **scale, affordability, and inclusivity** — enabling not only operators but also enterprises, governments, and societies to benefit from the 6G era.

9. Spectrum Roadmap

9.1 Unified Perspective on 6G Spectrum

6G will not rely on a single “magic band.” Instead, it will harness a **multi-layered spectrum fabric,** where each frequency range plays a distinct and complementary role:

- **Sub-7 GHz:** The foundational coverage layer, ensuring universal reach, mobility continuity, and reliable control signaling.
- **FR3 (7–24 GHz):** The primary new capacity layer of 6G, balancing coverage and throughput, suitable for macro and suburban deployments.
- **mmWave (24–100 GHz):** The extreme-capacity augmentation layer, ideal for dense urban hotspots, FWA, and enterprise broadband.
- **Sub-THz/THz (>100 GHz):** The transformative frontier, enabling Tbps-class localized experiences such as holographic telepresence, multi-sensory XR, and high-precision sensing.
- **Backhaul:** The glue that binds it all together, with fiber as the anchor and RF/FSO/sub-THz providing agility and scalability.

9.2 Spectrum Roadmap Timeline

2025–2030 (5G-Advanced → early 6G pre-standardization):

- Refarming of 2G/3G bands into modern IMT.
- Commercialization of **upper 6 GHz** (6425–7125 MHz).
- Continued rollout of mmWave (26/28/39 GHz) for FWA and hotspots.
- Initial **E-band (71–86 GHz)** expansion for backhaul.

2030–2035 (Early 6G deployments):

- **FR3 (7–8.5 GHz)** allocations crystallize; early deployments on existing macro grids.
- **Mid-FR3 (10–15 GHz)** pilots in urban/suburban capacity networks.
- Scaling of mmWave deployments, especially for enterprises and private 6G networks.
- **Sub-THz testbeds** move toward commercial pilots (100–140 GHz).
- AI-driven hybrid backhaul using fiber + E-band + FSO.

Beyond 2035 (Mature 6G ecosystem):

- Broader adoption of **upper FR3 (15–24 GHz)** and selected **Sub-THz bands (140–300 GHz).**
- Localized **THz (>0.3 THz)** links for Tbps services in specialized environments.
- Highly dynamic, AI/ML-driven spectrum orchestration across all layers.
- Integration of terrestrial and non-terrestrial backhaul (LEO/GEO satellites, HAPS, FSO).

10. Conclusion

The path to 6G will be defined by **how effectively we harness spectrum across all fronts**, ultimately leading to an **omni-band paradigm** . Low bands will remain indispensable for universal coverage and control, while **FR3 and sub-THz/THz stand out as the most strategic new candidates** for 6G deployment. Within FR3, the **7–15 GHz** range is especially promising for macro-cellular deployments that demand both reach and capacity; the **15–24 GHz** range suits **dense urban nodes and indoor hotspots.** This balance makes FR3 the **likely workhorse of nationwide 6G**, capable of delivering multi-gigabit mobility and immersive services at scale. Beyond FR3, **sub-THz and THz** spectrum becomes the **critical enabler of the most transformative applications:** by unlocking terabit-per-second links, these bands support **human-realistic holography, multi-sensor XR, and cyber-physical services**, redefining the role of mobile networks in society. In parallel, **fiber, RF, and optical-wireless (FSO) backhaul** must evolve into a resilient, elastic transport fabric that can sustain these unprecedented demands. Together, this blend of **spectrum and infrastructure** underpins the **intelligent, immersive, and inclusive** networks envisioned for 6G.

Yet **spectrum availability alone will not guarantee success**. The transition to FR3 and THz hinges on a new generation of **enabling technologies** that overcome their physical-layer realities. In **FR3**, the hybrid **near- and far-field** regime demands **regime-aware hybrid beamforming, RIS-assisted coverage shaping, and predictive (AI-driven) beam management** to maintain performance amid spatial non-stationarity, visibility-region fragmentation, and sub-band-dependent multipath. At the THz frontier, we will rely on **electronics- and photonics-based front-ends** (and hybrids), **extra-large MIMO arrays with spherical (near-field) beamforming, and frequency-/distance-aware link adaptation** to work within atmospheric absorption windows and close practical link budgets at Tbps rates.

Equally, **policy and harmonization** will pace deployment. WRC-aligned, regionally harmonized **FR3** bands are essential to achieve device scale and reasonable cost; **sub-THz windows** must be prepared with solid coexistence evidence and testbed data ahead of standardization cycles. **Security and sustainability** are not afterthoughts:FR1 should remain the hardened control anchor; end-to-end encryption, anomaly detection, and quantum-resilient cryptography must span FR3/mmWave/THz access and backhaul; and operators should target year-on-year energy-per-bit reductions through AI-assisted power scaling, sleep modes, and RIS-aided coverage.

Finally, **capacity is half access, half transport.** The durable pattern is **fiber-first**, augmented by **E-/D-band** and early **sub-THz** spurs, plus **coherent FSO** for trench-free, license-exempt rooftop spans—**all orchestrated** so the transport plane feels elastic to the RAN: always enough, always on, always efficient. **IAB** will cut site costs in dense grids, while multi-connectivity keeps sessions reliable as devices opportunistically burst into mmWave or THz when—and only when—it pays off.

Bottom line: 6G's step change will come from the **co-design** of spectrum layers, enabling technologies, and hybrid backhaul — not from any single band or headline peak rate. By aligning **FR1 for coverage and control**, **FR3 as the macro-scalable capacity layer, mmWave for surgical densification, and THz for the most demanding, sensing-native applications,** we can build a6G fabric that is **adaptive, resilient, and efficient**—ready to carry the next wave of applications from **extended reality to holographic communications and large-scale digital twins.**

A Concise Action Agenda (next 24–36 months)

- **Secure and harmonize FR3** contiguous blocks; run XL-MIMO, regime-aware field trials on live macro grids.
- **Right-size mmWave** with multi-connectivity; deploy only where KPIs (venue density, FWA corridors) justify it.
- **Advance THz responsibly:** focus on validated windows, near-field beamforming, and distance/frequency-aware adaptation; prioritize pilots where sensing + capacity create clear value.
- **Develop multi-band front-end platforms** to harness diverse frequency segments, ultimately converging toward an **omni-band paradigm** that unifies spectrum use across all fronts.Hybrid **backhaul at scale:** fiber first; add **E-band/D-band, coherent FSO,** and **sub-THz** spurs; implement **FSO ↔ RF** failover/aggregation.
- **Build in security & sustainability:** FR1-anchored control, E2E encryption and anomaly detection, **quantum-safe** roadmap; track watts/bit and deploy RIS/ sleep policies as standard practice.
- **Contribute to policy:** feed coexistence data into **WRC-27 → WRC-31**; advocate regional alignment to unlock device ecosystems and lower TCO.

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