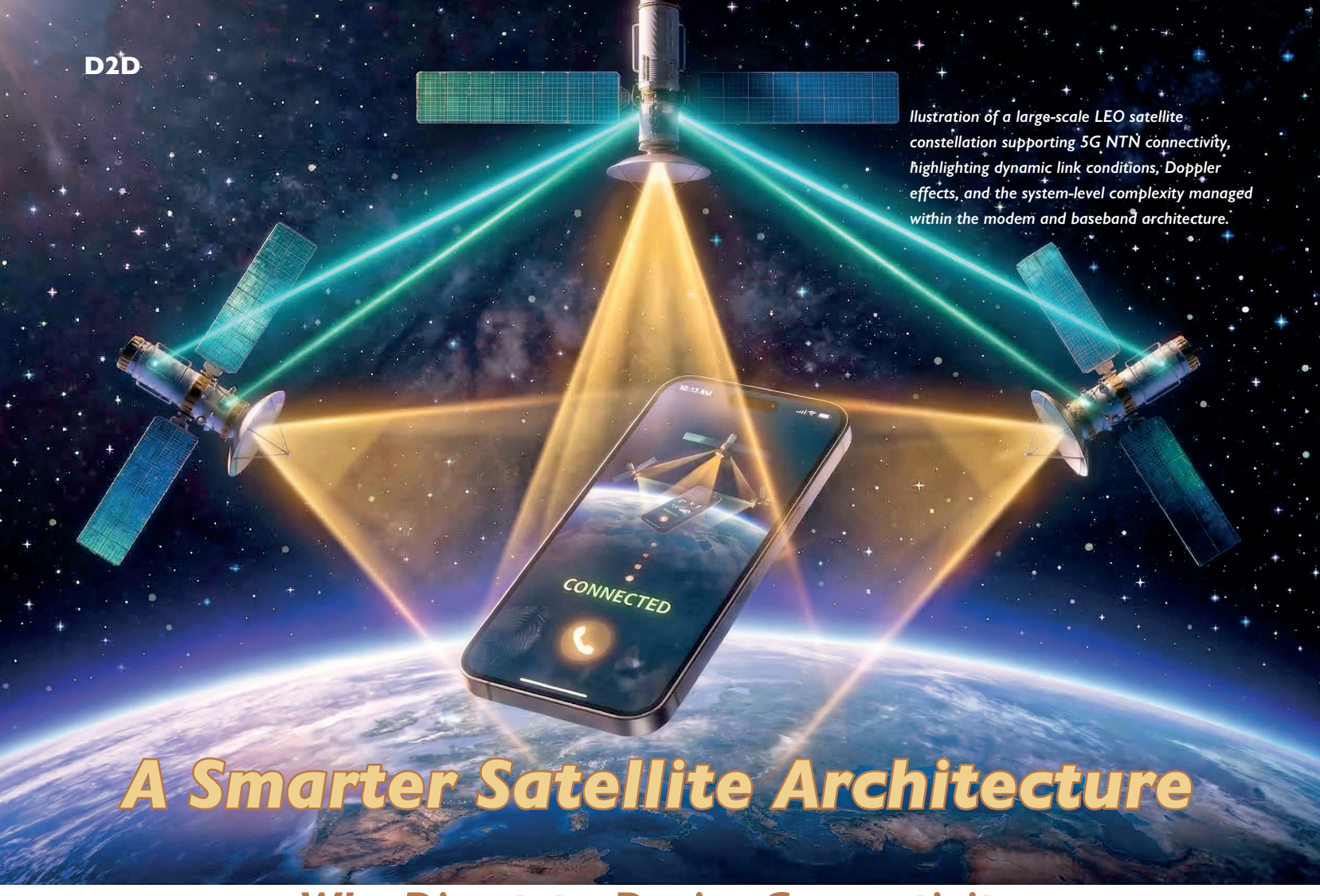


Illustration of a large-scale LEO satellite constellation supporting 5G NTN connectivity, highlighting dynamic link conditions, Doppler effects, and the system-level complexity managed within the modem and baseband architecture.

A Smarter Satellite Architecture

Why Direct-to-Device Connectivity Is Redefining the Satellite Modem

For decades, satellite communications and terrestrial cellular networks evolved along largely separate technological and economic paths.

Satellite systems relied on proprietary standards, specialized terminals, and vertically integrated infrastructure. Meanwhile, cellular networks developed within the standardized ecosystem defined by 3GPP, powering billions of smartphones and connected devices worldwide.

That separation is now breaking down quickly.

The introduction of 5G Non-Terrestrial Network (NTN) standards is enabling satellites to integrate directly into the global mobile network, transforming what was once a parallel infrastructure into an extension of the cellular ecosystem.

This shift opens the door to direct-to-device (D2D) and direct-to-cell (D2C) connectivity, allowing standard cellular devices to connect to satellites without specialized hardware.

The concept of satellite connectivity is not new, but the architectural implications of this transition are significant. Satellites are no longer just coverage extensions for remote areas. They are increasingly being designed as active components of the global mobile network.

This shift is redefining what must happen inside the satellite modem.

From Transparent Relays to Regenerative Satellites

Historically, most communications satellites functioned as transparent payloads. In this model, the satellite acts as a relay. Signals transmitted from the ground are received, amplified, and retransmitted back to Earth without significant onboard processing. The intelligence of the network remains primarily in terrestrial infrastructure.

Today, that model is evolving. New satellite constellations are increasingly adopting regenerative architectures, where satellites decode, process, and route signals onboard before forwarding them. Instead of acting as simple repeaters, satellites become active nodes in the communications network.

Several industry forces are accelerating this transition:

Declining launch costs
Large-scale low-Earth-orbit (LEO) constellations
Adoption of standardized 3GPP cellular protocols
Growing demand for ubiquitous mobile connectivity

According to Novaspace, the global space economy is expected to grow from approximately $626 billion in 2025 to over $1 trillion by 2034, with direct-to-device connectivity emerging as a key growth area.

More important than market projections, however, is the architectural shift. Once satellites become part of the cellular ecosystem, they must support the same baseband processing complexity as terrestrial mobile infrastructure.

Direct-to-Device Connectivity Introduces New Engineering Challenges

Connecting satellites directly to cellular devices fundamentally changes the modem problem.

Terrestrial cellular networks operate under relatively stable physical assumptions. Base stations are fixed. Devices move at limited speeds. Distances between devices and base stations typically range from hundreds of meters to a few kilometers. Satellite communication operates under very different conditions.

LEO satellites travel at roughly 7 to 8 kilometers per second, creating substantial and continuously changing Doppler shifts. Meanwhile, communication distances can exceed 1,000 kilometers, introducing propagation delays far beyond those assumed in conventional cellular systems. These conditions introduce several technical challenges that must be addressed within modem architecture.

Doppler Management
The rapid motion of satellites produces Doppler shifts that change continuously during a satellite pass. Managing this is no longer a link-level optimization.

It becomes a system-wide requirement within the modem architecture, requiring real-time tracking and compensation of frequency changes.

The challenge becomes more pronounced at higher RF frequencies. These are not minor parameter adjustments. They require rethinking how parts of the protocol stack behave under non-terrestrial conditions.

Timing and Protocol Adaptation
Many mechanisms in the 5G protocol stack were originally designed for terrestrial networks with relatively short propagation delays. Satellite links require adaptations to timing mechanisms such as Hybrid Automatic Repeat Request (HARQ) and other scheduling processes. These adaptations are defined within the 3GPP NTN specifications, but they still require sophisticated modem implementations.

Dynamic Network Topology
Unlike terrestrial networks with fixed base stations, LEO constellations involve satellites moving rapidly across the sky. Devices must continuously transition between satellites as coverage shifts. This creates additional requirements for tracking satellite position, managing handovers, and maintaining synchronization across a highly dynamic network topology. In effect, mobility shifts from being primarily a device problem to a network-wide coordination challenge.

Multi-Mode Interoperability
Direct-to-device systems must integrate satellite communication into existing cellular ecosystems. This requires modems capable of supporting both terrestrial and non-terrestrial communication modes while maintaining compatibility with evolving 3GPP standards.

The Architectural Balancing Act Inside the Modem

Designing a modem that can handle these challenges requires balancing several competing priorities.

On one hand, the signal-processing workload associated with modern cellular communications is highly demanding. Achieving the necessary performance and power efficiency often requires hardware acceleration for key baseband functions.

On the other hand, satellite systems must remain adaptable. Hardware deployed in orbit cannot easily be replaced, and communication standards continue to evolve. A modem architecture that is too rigid risks becoming obsolete long before the satellite reaches end of life.

One effective approach is a hybrid architecture that combines dedicated hardware acceleration with programmable processing resources.

Hardware acceleration handles mathematically intensive baseband functions such as channel coding, equalization, and physical-layer processing. Programmable DSP resources provide the flexibility to adapt algorithms and protocols as requirements evolve.

These elements are typically connected through a shared memory and interconnect structure that enables scalability across different NTN deployments.

This balance allows modem designers to achieve real-time performance while preserving the adaptability required for different orbits, waveforms, and future 3GPP releases.

This tension between performance and flexibility is not new. But in space, the consequences are far more significant. There are no field upgrades in orbit.

Why Satellite Operators Are Re-Thinking the Modem Stack

The complexity of NTN-compatible modem design is reshaping how satellite operators approach system development. Historically, many operators relied on large aerospace primes to deliver complete communication systems.

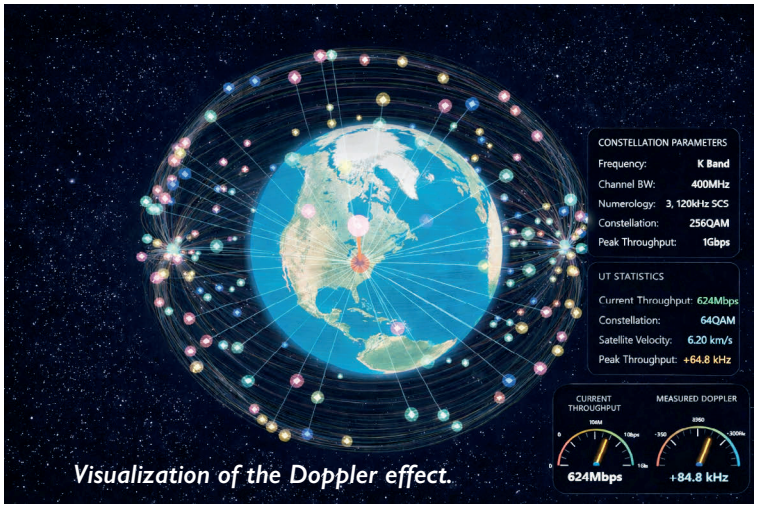
However, the rise of new commercial space companies and vertically integrated constellation operators has shifted this model. Many now seek greater control over their technology stacks while still accelerating time to deployment.

At the same time, building a cellular-grade modem from scratch represents a significant technical undertaking. Cellular modem technology has evolved over decades and embodies thousands of engineering years of accumulated development.

As satellite systems adopt 3GPP standards, operators are increasingly encountering this complexity for the first time. This dynamic is driving demand for integrated silicon IP platforms that can accelerate modem development while still allowing customization.

Platforms, such as Ceva's PentaG-NTN modem IP, illustrate this approach, providing a complete baseband processing subsystem designed for satellite user terminals and NTN deployments.

These platforms support 3GPP Release-18 NTN features, including adaptations for Doppler dynamics, extended timing windows, and integration with terrestrial cellular infrastructure. They also support both FR1 and FR2 spectrum, enabling flexibility across different satellite frequency bands and deployment models.



Visualization of the Doppler effect.

A Convergence of Two Engineering Worlds

Perhaps the most significant implication of NTN is that it brings together two historically distinct engineering ecosystems. Satellite engineers and cellular engineers have traditionally approached communications problems from very different perspectives. The adoption of 3GPP standards is merging those worlds.

As satellites become integrated into the cellular ecosystem, the complexity of cellular modem technology is moving into space. This includes advanced baseband processing, dynamic network management, interoperability with terrestrial infrastructure, and support for evolving wireless standards.

As this convergence accelerates, the distinction between terrestrial and non-terrestrial networks will continue to fade. Future wireless systems, including early visions of 6G, already assume deeper integration between satellite and terrestrial connectivity. In that context, satellites are no longer a separate communications system. They are part of the global network.

As that happens, the satellite modem becomes a core element of the cellular infrastructure stack, designed for a network that extends far beyond the Earth's surface.

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Elad Baram is Director of Product Marketing for the Mobile Broadband Business Unit at Ceva Inc., where he leads strategy and market development for next-generation connectivity solutions. He brings more than 15 years of experience in product leadership across AI, IoT, and embedded systems.

