Cable-Free Physical Layers for Rack-Scale AI/HPC Systems:

Timour Paltachev, D.Sc.Eng, Konstantin Tiutin, M.Sc.Eng

Contact: nazym@rivvor.com | timour@rivvor.com | konstantine@rivvor.com
101 Creekside Ridge Ct, Suite 210, Roseville, CA 95678 | rivvor.com | linkedin.com/company/rivvor-inc

MOTIVATION

AI and HPC clusters are hitting a hard constraint at the shortest range. Short-reach copper and optical links connecting accelerators within racks impose three compounding problems that cannot be resolved by tuning switches or adjusting routing protocols.

Performance layer. GPU stalls during collective operations (all-reduce, all-gather, reduce-scatter) are sensitive to tail latency, not average throughput. Cross-node latency directly reduces tokens per second. p99/p999 latency is fixed in the physical layer.

Network layer. Static topologies defined at installation time cannot adapt to dynamic workload patterns. No path diversity means congestion propagates directly into job slowdown. Scaling cost grows non-linearly with accelerator density.

Physical layer. Dense cable harnesses obstruct airflow and increase thermal stress. Cable-related issues account for nearly 50% of data center troubleshooting time. Over 60% of outages exceed $100K in losses. Complex AI facilities typically require 24 to 36 months from concept to commissioning, with cabling complexity as the primary scheduling constraint.

WHY SUB-THZ WIRELESS NOW

Recent advances in mmWave and sub-terahertz RF circuits make intra-rack wireless a practical physical layer option today. Unlike wide-area wireless, intra-rack deployments operate over fixed geometries, short distances, and engineered line-of-sight paths. These conditions allow deterministic, interference-free operation by design.

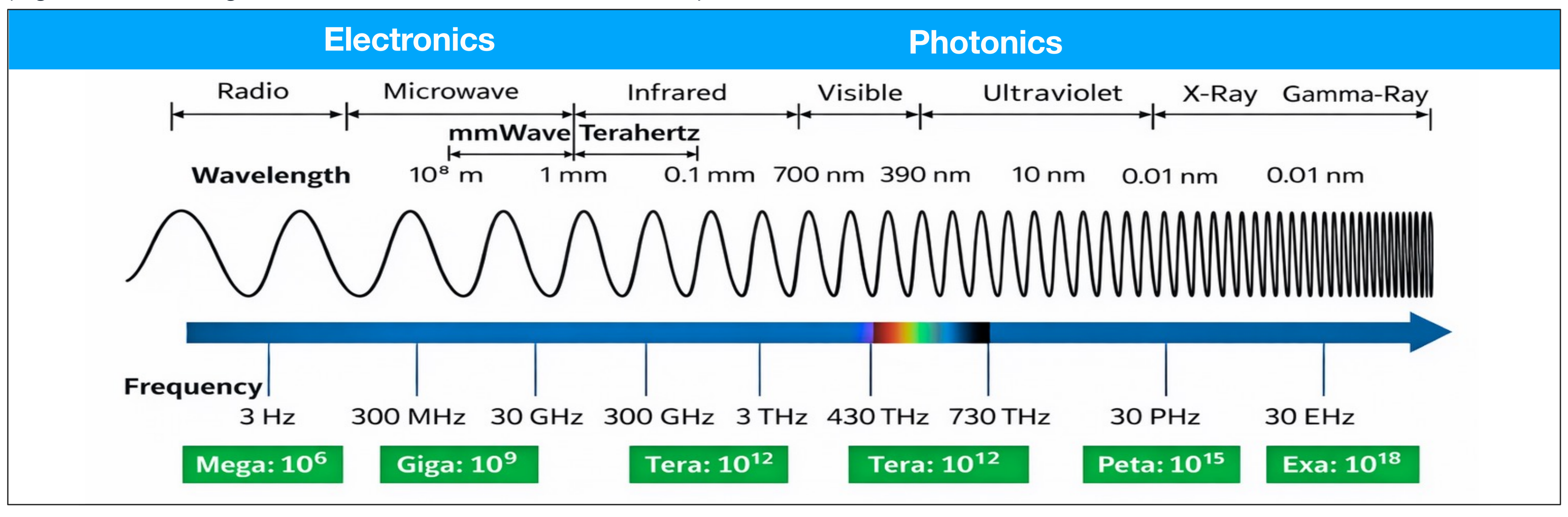
At 150-450 GHz, wavelengths of 0.67-2.0 mm allow high-gain antenna arrays to fit within standard server blade dimensions. At a 25 mm aperture, beamwidth narrows from 4.6 degrees at 150 GHz to 1.53 degrees at 450 GHz, enabling precise spatial targeting and spatial reuse without interference. Strong path loss at these frequencies naturally confines links within the rack enclosure.

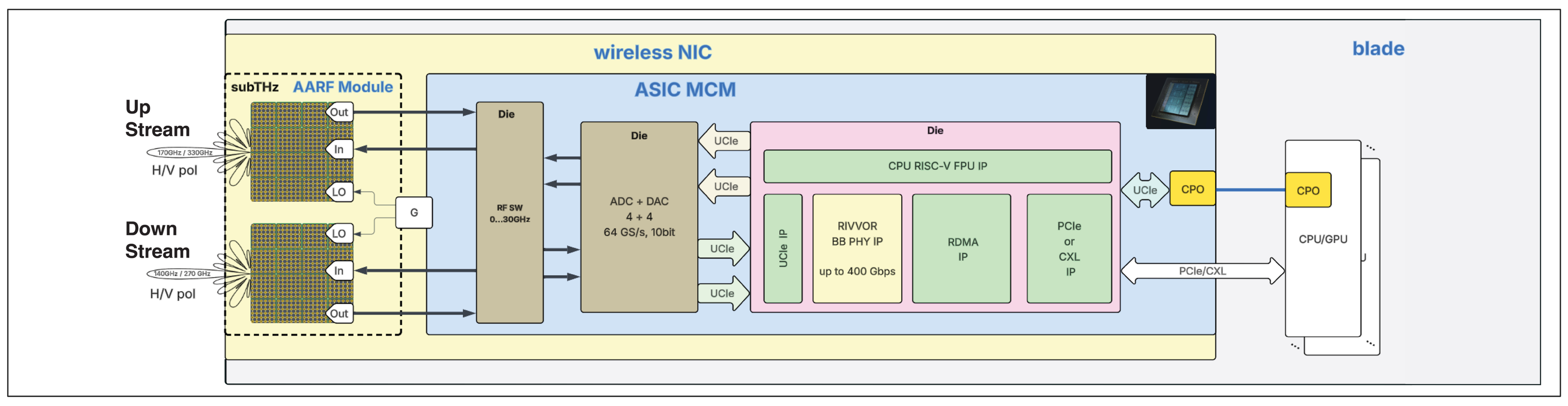
Integrated low-power sub-THz RF is now practical in SiGe, CMOS, and InP processes. The FCC's 2019 Spectrum Horizons framework established unlicensed operation across 21.2 GHz of spectrum above 95 GHz. For enclosed intra-rack deployments at short-range power levels, the regulatory path is well-defined.

Table 1 - Wavelength vs Antenna size vs Beam Size

Frequency, GHZ	Wavelength, mm	Antenna Size (D),mm	Beamwidth (deg)	Gain (dBi)
150	2.00	25 (<1U)	4.6°	~32
250	1.20	20 (<1U)	3.4°	~35
350	0.86	15 <1U)	3.3°	~35
450	0.67	15 (<1U)	2.5°	~37

(Figure 1: Wavelength vs Antenna Size vs Beamwidth table)





Target specifications	
Parameter	**Target**
Beamwidth	< 3 degrees
Frequency	Up to 1 THz
One-way E2E latency	< 0.5 µs
BER	≤ 1e-15
Full duplex bandwidth	Up to 1 Tbps
Host interface	PCIe, CXL
Modulation	FDD, MIMO 2x2

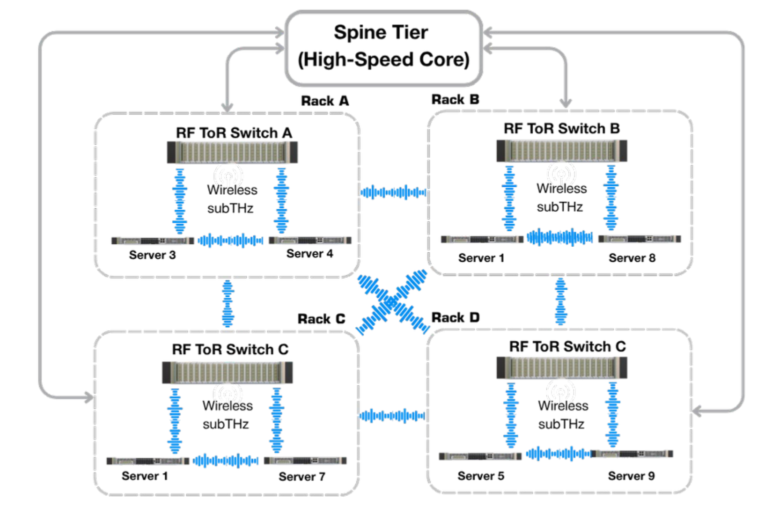
ARCHITECTURE

Rivvor replaces short-reach copper cabling with directional sub-THz links inside enclosed rack environments. The physical layer becomes software-defined.

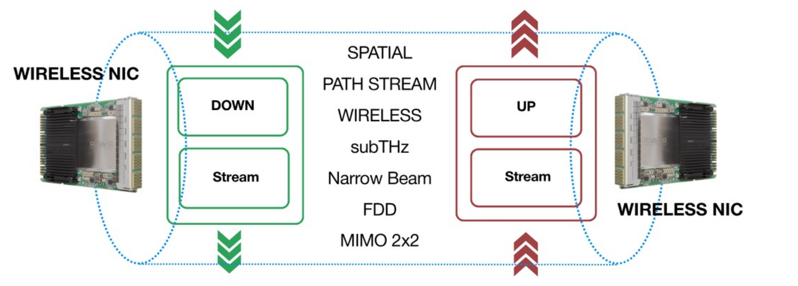
Wireless NIC. Each compute node integrates baseband processing, an RF front-end operating up to 1 THz, and MIMO 2x2 / FDD beamforming. Links operate over 1-2 m within the rack. PCIe and CXL host interfaces preserve compatibility with existing infrastructure. RDMA coherent memory access is supported.

Minimal-hop fabric. Traditional NIC-to-switch-to-NIC paths introduce arbitration, queueing, and buffer-induced latency variance. Single-hop direct node-to-node wireless links eliminate intermediate buffering from the latency-critical synchronization path entirely.

RF ToR orchestration. A wireless Top-of-Rack switch orchestrates rack connectivity, manages traffic-aware multi-path routing, and integrates with the spine network.



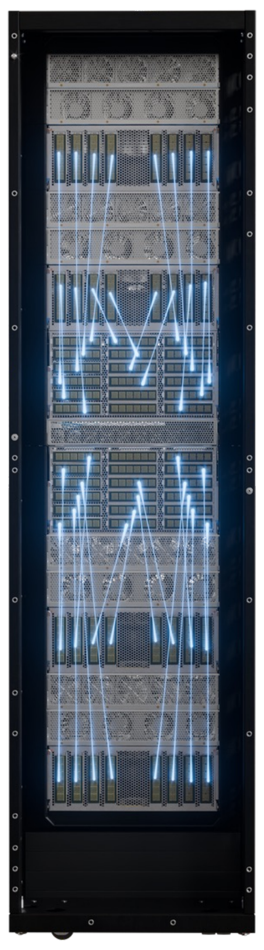
(Figure2 : Multi-rack programmable fabric topology diagram with RF ToR switches)



(Figure 3: Wireless NIC link diagram showing spatial path streams)

EXPERIMENTAL RESULTS

An initial system-level prototype was implemented using FPGA-based baseband processing and mmWave/sub-THz RF front-ends, validating the core architectural elements under realistic rack-scale conditions.
CALLOUT: Measured one-way end-to-end latency: 1.5 µs. Single rack, mmWave, enclosed environment.



2025 — Complete. Single rack, mmWave, 1 simultaneous link. RF-link validated at 1.5 µs, measured one-way latency. Enclosed environment validation and signal stability confirmed.

2026 — In Progress. Single rack, sub-THz, 4 simultaneous links. Active validation targets: bounded latency below 1.5 µs one-way, BER at 1e-12, stable operation, zero-flap link switching, and interference resilience within the rack.

2027 — Planned. Multi-rack sub-THz fabric, 10 simultaneous links, workload-driven traffic. PCIe/CXL traffic model alignment, OCP NIC concept integration, stable scaling across multi-rack RF topology.

Direct node-to-node communication, elimination of intermediate switching from the critical datapath, and dynamic link establishment and release have all been confirmed in prototype testing.

IMPLICATIONS FOR OPEN DATA CENTER DESIGN

Cable-free physical layers enable new rack architectures built around modularity, improved airflow, and robotic serviceability. Decoupling physical placement from communication topology enables:

Autonomous deployment with zero-cable-touch buildout and remote reconfiguration. Standardized, repeatable rack designs with no custom wiring. Dynamic link activation aligned with workload demand, reducing always-on interconnect power during idle periods. Improved thermal performance and reduced OPEX at scale. Faster scaling and upgrades with minimal physical intervention.

Rivvor's wireless fabric does not replace long-range optical transport. It addresses the specific regime where static physical mediums impose the greatest cost: the innermost layer of enclosed, high-density AI compute systems.