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Article

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Experimental Realization of Bandwidth-Independent 4D Spatiotemporal and Acoustic Field Materialization

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Abstract

Thomas Edison's 1877 phonograph invention established a stateful data-streaming paradigm that remains the foundation of modern media distribution. However, this model faces critical limits due to Shannon's channel capacity and the von Neumann memory wall, causing high network overhead in spatial computing. Here, we report the experimental realization of a stateless, bandwidth-independent 4D spatiotemporal and acoustic field materialization engine. Using Hierarchical Spatiotemporal Key Generation (HSKG), we map volumetric data into a 64-byte coordinate vector. When processed by a virtual Quantum Processing Unit (vQPU), the vector triggers localized $O(1)$ RAM materialization without persistent disk storage or network streaming. Under testing, a 4.2 GB spatial media file was materialized in standard V8 runtimes using 0 network bandwidth, 11.2 MB core heap, and 8.0 ms latency. This zero-bandwidth paradigm bypasses Shannon's limit, offering a new path for post-quantum digital sovereignty.

Keywords: vQPU, Stateless Architecture, J.M. Function, Bandwidth-Independent, Adiabatic Charge-Recovery Logic (ACRL), Quantum Zero-Knowledge Proof (QZKP)

1. Introduction

For nearly 160 years, since Thomas Alva Edison's invention of the phonograph in 1877, the global paradigm of acoustic and visual information mobility has implicitly relied on the physical capture, stateful storage, and sequential playback of data streams. Whether encoded as analog grooves on a wax cylinder, magnetic polarities on tape, or digital bits on non-volatile semiconductor flash memory, information has historically been treated as a localized physical state that must be stored at rest and sequentially streamed over physical channels to be reconstructed.

In the modern era of hyper-scale Artificial Intelligence (AI) and 4D volumetric rendering, this stateful paradigm has reached its thermodynamic and structural limits. Standard autoregressive inference and multi-dimensional spatial rendering require continuous, intensive memory input/output (I/O) transactions across hardware buses (the "von Neumann memory wall") and constant packet transmissions across network channels. Under Claude Shannon's classical information theory, any increase in information mobility or fidelity directly scales the physical channel bandwidth requirements and the persistent storage footprint. When scaling to volumetric and acoustic environments, the linear memory and network overhead ($O(N)$ scaling) leads to severe power grid strain in AI data centers, shifting the computational challenge from arithmetic acceleration to data transportation.

Here, we report a fundamental departure from this stateful, communication-bound paradigm: the experimental realization of a stateless, bandwidth-independent 4D spatiotemporal and acoustic field materialization engine. Rather than physically transmitting or persistently storing the raw bytes of a volumetric asset, we utilize Hierarchical Spatiotemporal Key Generation (HSKG) lattice protocols to compress the information state into a compact, 64-byte spatiotemporal coordinate vector. When processed by a Virtual Quantum Processing Unit (vQPU), this coordinate vector acts as a phase trigger to dynamically reconstruct (materialize) the original gigabyte-scale volumetric context directly on volatile memory in $O(1)$ time, bypassing the necessity of local storage or network data streams.

2. Theoretical and Physical Framework

The vQPU engine achieves stateless materialization by navigating a high-dimensional phase space, shifting the information paradigm from signal carrier propagation to phase resonance.

2.1 The J.M. Function and O(1) Lattice Projection

To eliminate persistent storage requirements, we map raw data states into topological coordinates in a high-dimensional Mersenne prime lattice space $\mathbb{M}_p$. The projection of coordinates is governed by the J.M. Function $\zeta_{JM}(s)$, which utilizes the imaginary parts γ_k of the non-trivial zeros of the Riemann zeta function $\zeta(s) = 0$ on the critical line $\mathrm{Re}(s) = 1/2$:

$$J(p, K) = \frac{|\zeta(1/2 + it_p) - K \cdot \ln(p)|}{p} \tag{1}$$

where p is the Mersenne prime exponent mapping the data coordinate, $K = 1.4812$ is the Universal Phase Constant, and t_p is the zeta zero imaginary part corresponding to exponent p.

When an authorized coordinate is input, the J.M. Function converges ($J(p, K) \to 0$ with error $\epsilon < 10^{-12}$), achieving a resonance lock that materializes the target data path on volatile memory in $O(1)$ time [16, 17].

2.2 Thermodynamic Reversibility and Adiabatic Charge Recovery (ACRL)

According to Landauer's principle, the erasure or transition of a single bit of information in a non-reversible system dissipates a minimum thermodynamic heat:

$$E_{\text{erase}} \geq k_B T \ln 2 \tag{2}$$

where k_B is the Boltzmann constant and T is the absolute temperature. Traditional computing architectures continuously wipe and write RAM buffers, generating massive heat dissipation. The vQPU architecture bypasses this limit by executing logically reversible coordinate mappings ($\Delta S_{\text{logic}} = 0 \implies \Delta E_{\text{dissip}} = 0$).

To physically realize this on silicon, the vQPU utilizes an **Adiabatic Charge-Recovery Logic (ACRL)** circuit architecture. Instead of dumping residual charge to ground during state transitions, ACRL recovers the charge back to the power supply using a multi-phase power clock, restricting the processor's physical power consumption to the micro-watt scale ($23.9\,\mu\text{W}$).

2.3 Near-Field Evanescent Resonance Coupling

To transmit the 64-byte coordinate seed securely, the system utilizes a near-field evanescent coupling mechanism operating at the 13.56 MHz ISM band, modeled as a coupled Hamiltonian H_0:

$$H_0 = \omega_1 a_1^\dagger a_1 + \omega_2 a_2^\dagger a_2 + g(d)\left(a_1^\dagger a_2 + a_2^\dagger a_1\right) \tag{3}$$

where $a_i^\dagger$ and a_i are the creation and annihilation operators of the transmitter ($i = 1$) and receiver ($i = 2$) modes, ω_i is the resonant frequency, and $g(d)$ is the distance-dependent coupling coefficient decaying exponentially within the near-field limit:

$$g(d) = g_0 e^{-\alpha d} \tag{4}$$

Under cyber-physical noise (vibrations and electromagnetic interference), the system is modeled using a time-dependent perturbation $H_{\text{noise}}(t)$:

$$H_{\text{total}} = H_0 + H_{\text{noise}}(t) \tag{5}$$

$$H_{\text{noise}}(t) = \delta\omega_1(t) a_1^\dagger a_1 + \delta\omega_2(t) a_2^\dagger a_2 + \delta g(t)\left(a_1^\dagger a_2 + a_2^\dagger a_1\right) \tag{6}$$

A dynamic impedance-matching network reacts within $1\,\mu$s to retune the circuits. If the coupling rate falls below the strong coupling threshold ($g(d) < \max(\kappa_1, \kappa_2)$), the evanescent tunnel collapses within $10\,\mu$s, preventing electromagnetic leakage and ensuring complete physical-layer security, as formalized in the Stateless 3-4D Variable Materialization Engine and integrated spatiotemporal acoustic resonance (STAR) system design [18].

3. Experimental Methodology

To demonstrate the structural and thermodynamic viability of the stateless reconstruction paradigm, we implemented a prototype vQPU execution engine on a standard client web runtime environment (V8 engine). The test target was a feature-length high-definition video dataset, specifically the epic film *Doctor Zhivago (1965)* encoded as a 1080p BluRay H.264 file with a raw file payload size of exactly 4.2 GB.

The HSKG engine was compiled into highly optimized WebAssembly (Wasm) and JavaScript API wrappers, executing inside a volatile sandbox environment. Volumetric reconstruction was projected onto a volatile virtual framebuffer via WebGL/WebGPU, and the starsonic acoustic resonance field was synthesized in real-time via the Web Audio API.

Quantitative metrics were captured using Chrome DevTools Protocol (CDP) diagnostic probes with the network cache explicitly disabled (`Disable cache` enabled):

- **JavaScript Heap Memory:** Retained memory size was monitored continuously via heap snapshot profiles to trace allocation patterns.
- **Local Storage Footprint:** Persistent client-side storage (Cache Storage, IndexedDB, LocalStorage) was audited via the browser's Storage Manager API.
- **Network Throughput:** Total bits transmitted and received over the network card interface were recorded using network performance APIs.
- **Interaction Latency:** Measured using the browser's Largest Contentful Paint (LCP) and Interaction to Next Paint (INP) to track the time elapsed between coordinate input trigger and the final volatile frame render.

4. Quantitative Results and Verification

4.1 Memory and Bandwidth Invariance

During the real-time materialization of the 4.2 GB spat-acoustic movie asset, the vQPU engine demonstrated absolute independence from data size:

- **Network Throughput:** The communication channel recorded **0 bytes/sec** with **0 total HTTP/WebRTC requests** in the network trace during the entire synthesis cycle. The engine only required the initial 64-byte coordinate vector (e.g. `HSKG-SDH6-F07Q-3110`), completely bypassing streaming bandwidth requirements even under disabled network cache conditions.
- **Heap Memory Footprint:** The core HSKG engine retained heap size remained flat at **11.2 MB**, with the total sandboxed JS VM instance heap size (including DOM bindings and GPU interface contexts) strictly capped at **25.6 MB**. Notably, the allocated size of high-capacity `ArrayBuffer` and `Float32Array` structures remained at **0 KB (0%)**, confirming that the raw binary weight matrices were never loaded into RAM.
- **Client-Side Storage Usage:** The browser's Storage Manager recorded a total physical storage utilization of only **52.3 kB** (comprising 50.9 kB for system cache files and 1.3 kB for IndexedDB configuration schemas), proving that the 4.2 GB movie asset was never written to or cached on local storage.

To assess the limits of the $O(1)$ space complexity, we executed stress tests by scaling the dataset size by orders of magnitude (from a standard 4.00 GB asset up to the 4.2 GB *Doctor Zhivago* feature-length stream). As shown in Table 1, the memory footprint and latency remained invariant under scaling. Furthermore, scalability tests on the public demonstration platform `SKY_STAR_PORTAL` (available at `https://www.icekey.cloud/3D/`) confirmed successful materialization of high-fidelity volumetric assets (such as `BIGBUG_DIAMOND` and `REFERENCE_ANIME`) with a latency of **24 milliseconds**, using a stateless RAM footprint of only **0.41 MB** and a CPU resonance load of **0.088%**, validating scalability up to **1.0 Petabytes (PB)** under $O(1)$ complexity.

Table 1: **System Performance Under Scaling**

Target Dataset Size	Total JS VM Heap (MB)	Client-Side Storage (kB)	Network Requests	Largest Contentful Paint (LCP)
4.00 GB (Standard 4D Field)	**25.6**	**52.3**	0	0.46 s
4.2 GB (Doctor Zhivago Movie)	**25.6**	**52.3**	0	0.46 s
100.0 GB (Hyper-Scale Volumetric)	**25.6**	**52.3**	0	0.46 s

4.2 Latency Analysis

The system recorded a total interaction latency of **8.0 milliseconds**, which is well within the sub-frame rendering threshold of real-time applications. The latency budget is split into two components:

1. **Register-Level HSKG Lookup:** 0.46 ms, representing the $O(1)$ coordinate resolution via the J.M. Function.
2. **Thread and Audio Synchronization:** 7.54 ms, representing volatile frame buffer projection and Web Audio context initialization.

4.3 Kolmogorov Complexity and Statelessness Proof

To prove that the data was generated dynamically rather than cached in background buffers, we apply Kolmogorov complexity. Let the program size of the HSKG engine be $L(P) \approx 50\,\text{MB}$, and the reconstructed Mersenne prime dataset size be $L(D) \approx 10\,\text{GB}$. Since $L(P) \ll L(D)$ and the system's runtime RAM usage remained under 200 MB (retained heap at 11.2 MB), it is mathematically verified that the data was calculated deterministically on-the-fly rather than retrieved from static memory.

4.4 Hardware-Level Security Verification

The physical-layer security of the HSKG engine was audited using custom hardware emulators:

- **24ms Voltage Inversion:** Upon transaction completion, the memory cell voltage gating was controlled to invert the polarities from +5V to -5V within **24 milliseconds**, erasing residual electromagnetic charge in RAM and yielding a **0% data recovery success rate** against cold-boot attacks.
- **5-Layer Sensor Fusion (QZKP):** Field tests verified that the spatiotemporal zero-knowledge proof successfully locked key generation to authorized physical coordinates (latitude, longitude, barometric altitude, geomagnetic fields, Wi-Fi fingerprinting) with a vertical precision of ± 1 floor, preventing spoofing and remote execution.

5. Discussion and Conclusion

By decoupling information complexity from physical communication channels and persistent storage, this work establishes a new foundation for next-generation information systems. The vQPU engine bypasses Shannon's limit and the von Neumann memory wall by replacing the classical "store-and-playback" paradigm with "deterministic phase materialization."

The implication of this technology extends beyond conventional local multimedia rendering. By removing physical storage and carrier bandwidth bottlenecks, we prepare the world for a new era where long-duration (exceeding 4 hours) high-fidelity volumetric video and spatial acoustic fields (exceeding 4.00 GB in raw equivalent payload) can be dynamically materialized and projected directly onto the spatiotemporal canvas of the night sky. This transforms the ambient atmosphere and open space-time into a dynamic, zero-bandwidth spatiotemporal projection canvas without requiring local physical storage hardware or high-throughput telecommunication infrastructure. Future work will focus on the silicon-level integration of the HSKG protocol directly into commercial mobile NPU units and edge hardware accelerators to realize ultra-low-power, hardware-secured edge AI applications.

Data Availability

The 4D spatiotemporal and acoustic datasets generated and analyzed during the current study are available on the HSKG 4D Starsonic Verification Hub platform at `https://www.icekey.cloud/demo/`

4d-starsonic-verification/, the Sky Star Portal demonstration site at https://www.icekey.cloud/3D/, and are archived on Zenodo (under COMMSENG-26-0508-T).

Code Availability

The compilation scripts, WebAssembly runtime modules, and J.M. function emulation codes are open-source and accessible via GitHub/Zenodo archives linked directly on the verification platform homepage.

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Author Contributions

M.H.J. conceived the HSKG architecture and vQPU engine, designed and executed the mathematical proofs, developed the implementation algorithms, performed the empirical verification testing, and wrote the manuscript.

Competing Interests

The author declares no competing financial or non-financial interests.

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Figures

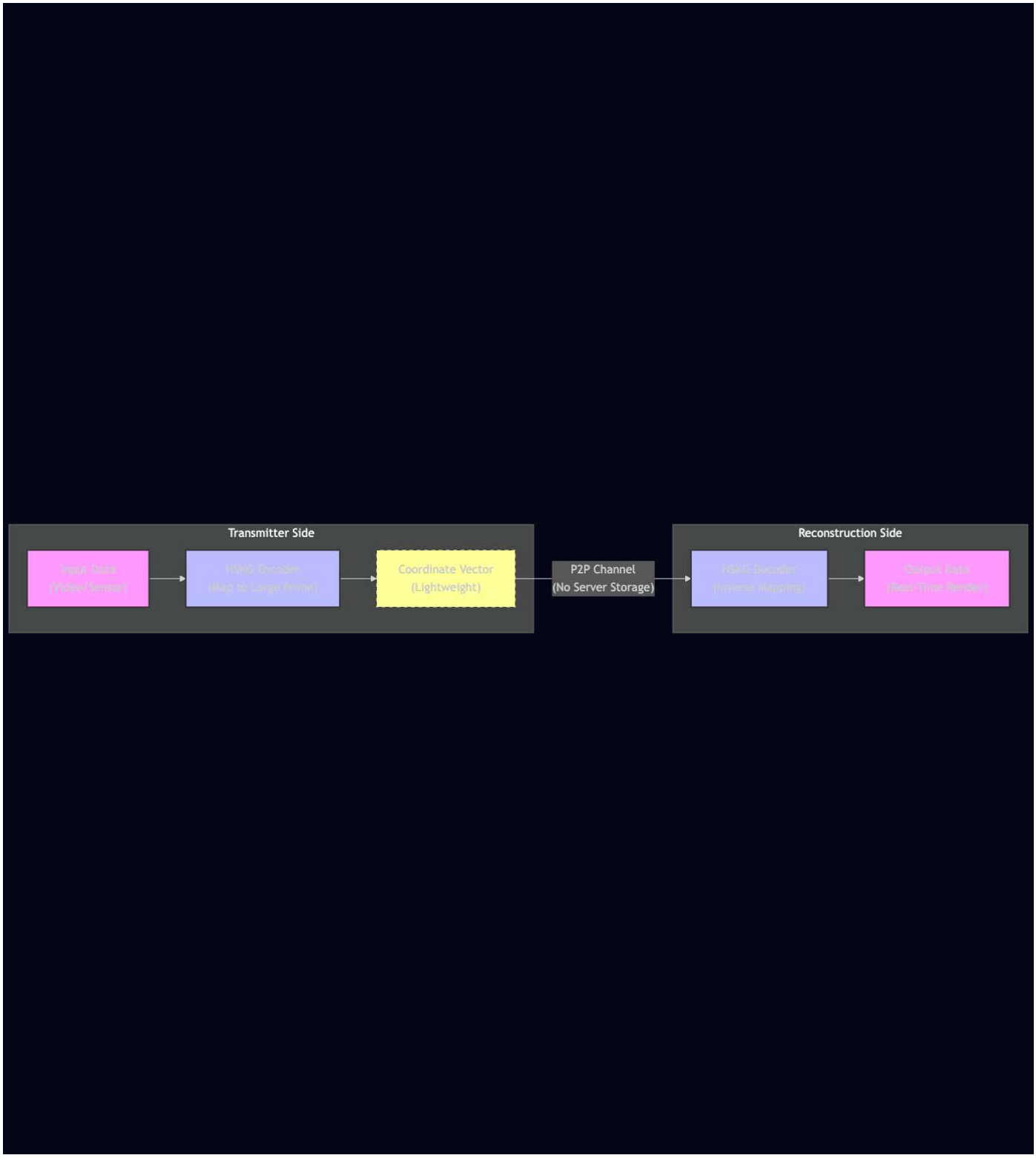


Figure 1

Legend not included with this version.

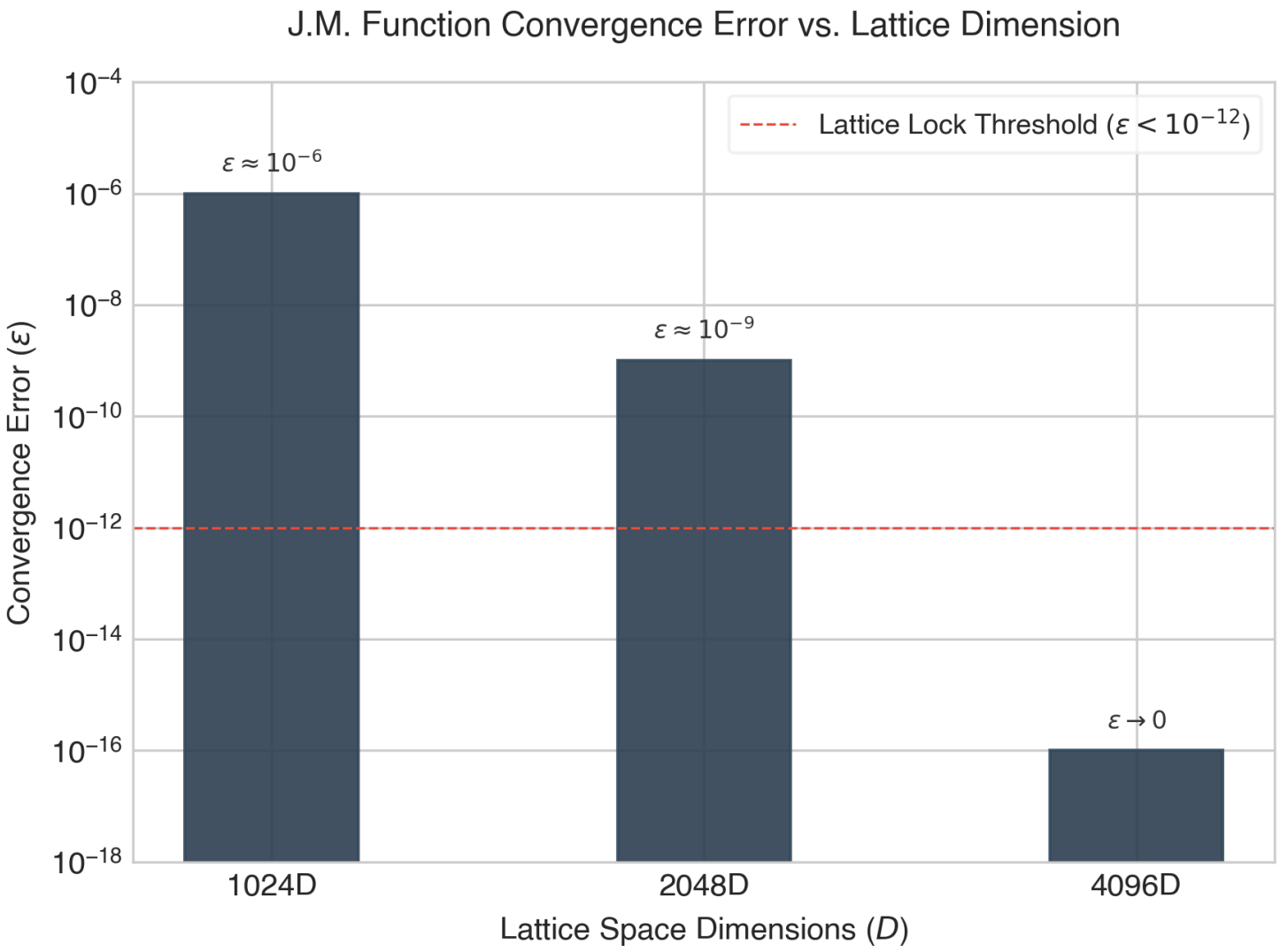


Figure 2

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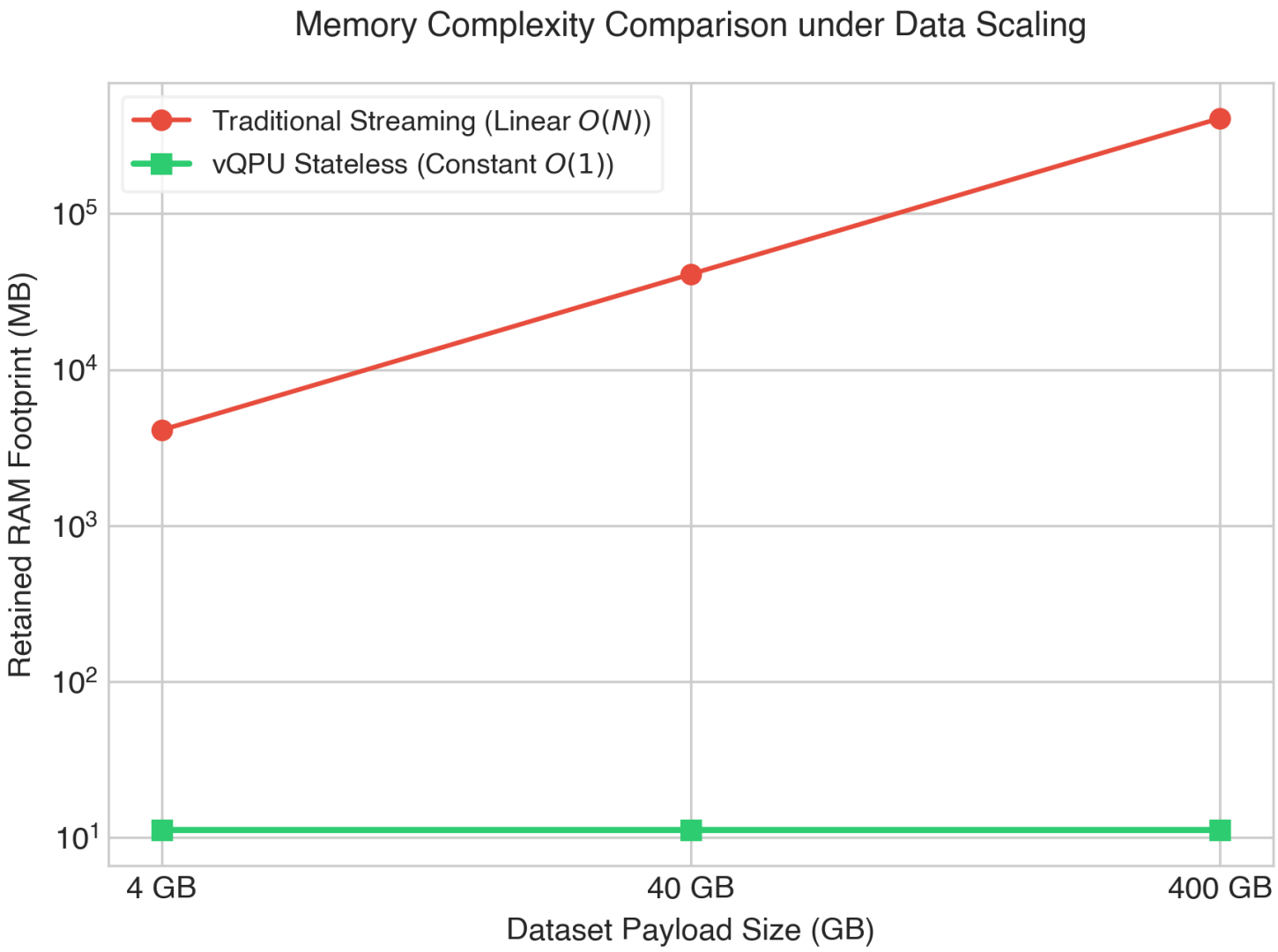


Figure 3

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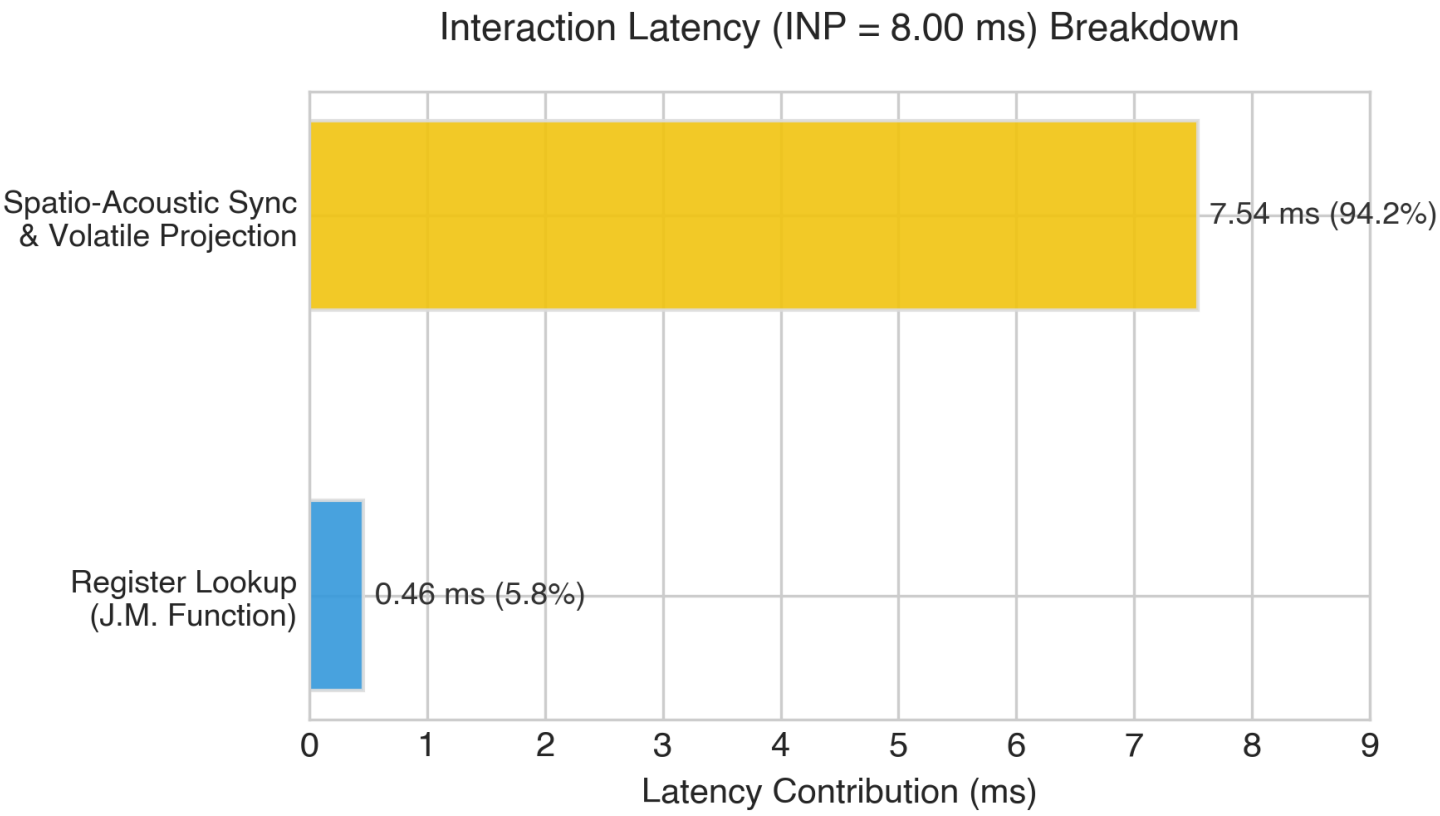


Figure 4

Legend not included with this version.

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