

Web3D 2026

Decentralized Storage, Distribution and Verifiable Retrieval of X3D Spatial Audio Scenes

Eftychia Lakka, Chrysoula Tzermia, Don Brutzman,
Athanasios G. Malamos, Evangelos K. Markakis

Hellenic Mediterranean University, Greece
Web3D Consortium

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Introduction

From **Web 3D Content** to **Immersive Experiences**

- Spatial audio is essential for presence and realism in virtual museums, cultural heritage, interactive performances, and metaverse environments
- X3D 4.0 provides a standardized, declarative representation of geometry, interaction, and spatial audio
- Modern immersive scenes are compositions of interconnected geometry, audio, behaviour, and multiple levels of detail
- These scenes increasingly require distributed and progressive web delivery

As immersive scenes become distributed, how can we preserve the experience exactly as authored?



Problem Definition

1 - A scene is not a single file

An X3D spatial audio scene combines 3D content, geometry, spatial audio, behaviour, and multiple Level of Detail (LOD) resources that must remain integrity consistent

2 - Delivery requires implicit trust

Traditional progressive-loading systems depend on centralized infrastructure, without content-level verification of each streamed fragment

3 - Existing technologies solve only part of the problem

- IPFS verifies content associated with a Content IDentifier (CID), but does not identify the author-authorized scene version
- Blockchain provides an authoritative reference, but cannot efficiently store and progressively deliver complete 3D scenes

Problem statement

A **unified** mechanism is needed to progressively deliver **X3D scene** fragments while verifying their **integrity** and **authorized** version before admission to the **live scene graph**

Proposed Approach

1 - Build and Package

- Decompose the X3D scene into a persistent shell and independently loadable LOD0 / LOD1 geometry chunks
- Generate a manifest with path, size, and SHA-256 digest of every fragment

2 - Publish and Anchor

- Publish the complete scene package as one content-addressed IPFS directory
- Store only the root CID in a minimal Ethereum smart contract
- Per-chunk hashes remain off-chain — minimal blockchain cost

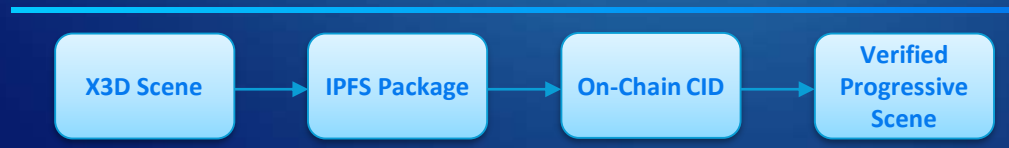
3 - Verify and Progressively Bind

- Retrieve the authoritative root CID from the contract
- Fetch manifest, shell, and LOD chunks
- Verify each fragment's SHA-256 digest before mounting in X_ITE
- Progressively upgrade: shell → LOD0 → LOD1(higher detail when needed)

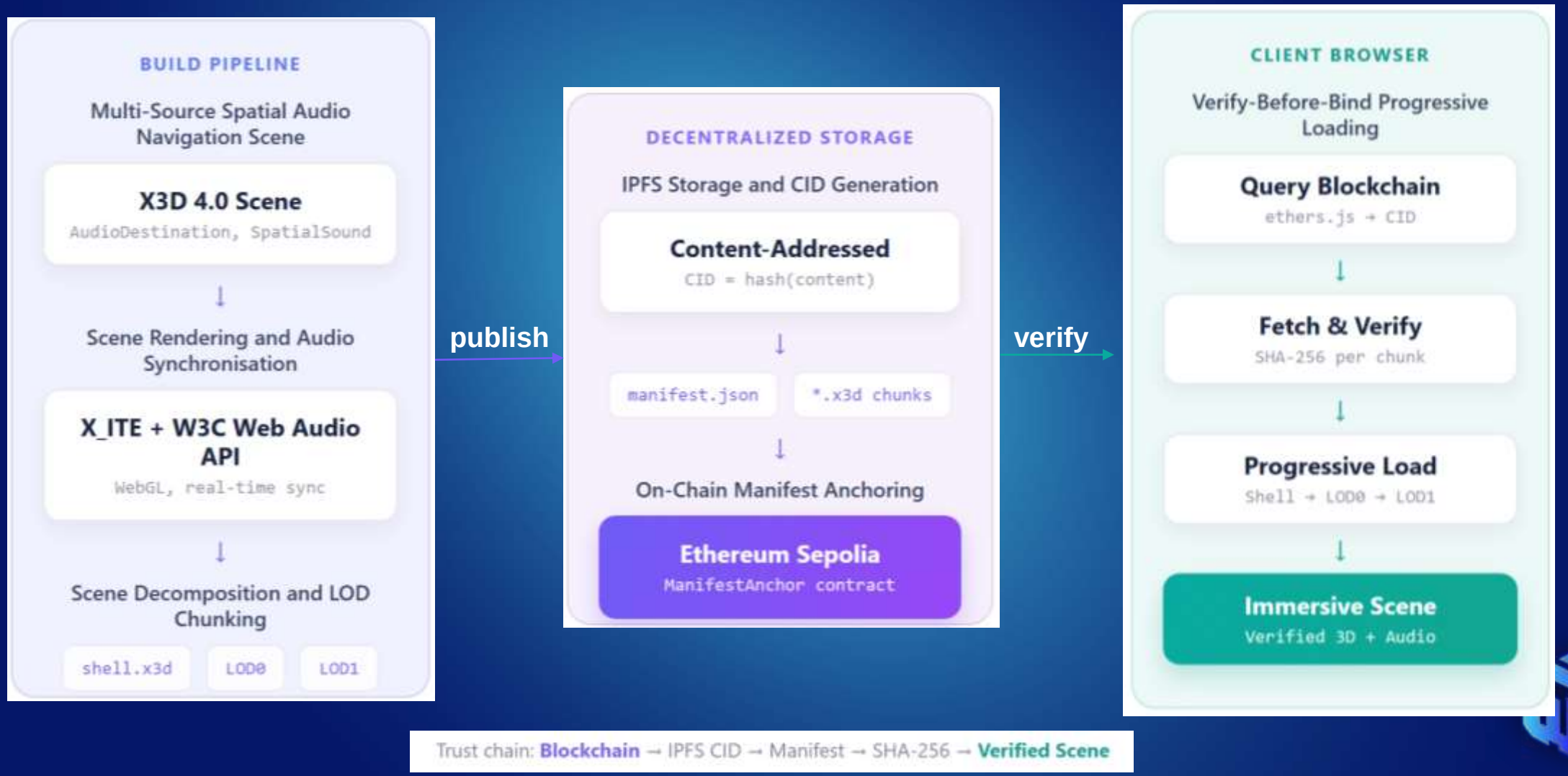
Core principle

Fetch → Verify → Bind

Unverified content **never** enters the live X3D scene graph



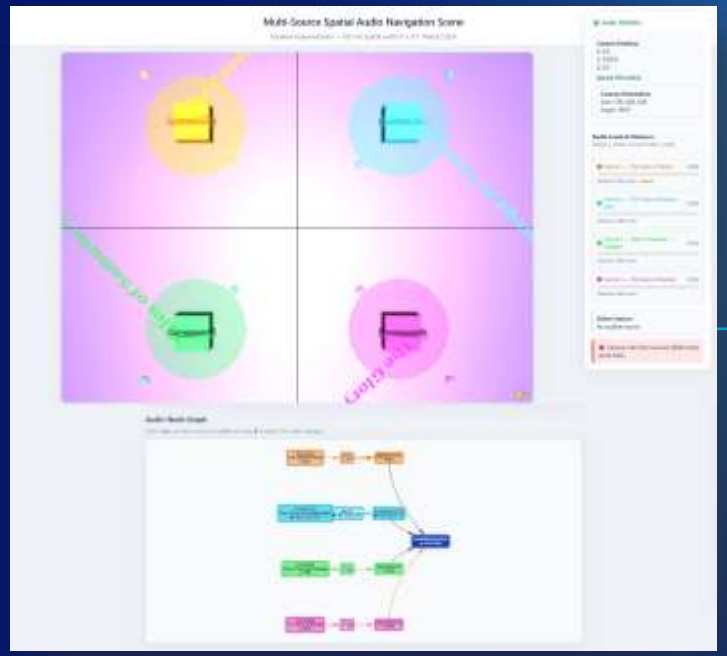
System Architecture



Trust chain: **Blockchain** → IPFS CID → Manifest → SHA-256 → **Verified Scene**

Prototype Implementation

BASELINE
Direct X3D Scene Loading



Direct loading of the complete X3D spatial-audio scene, with runtime statistics and X3D Audio Node Graph

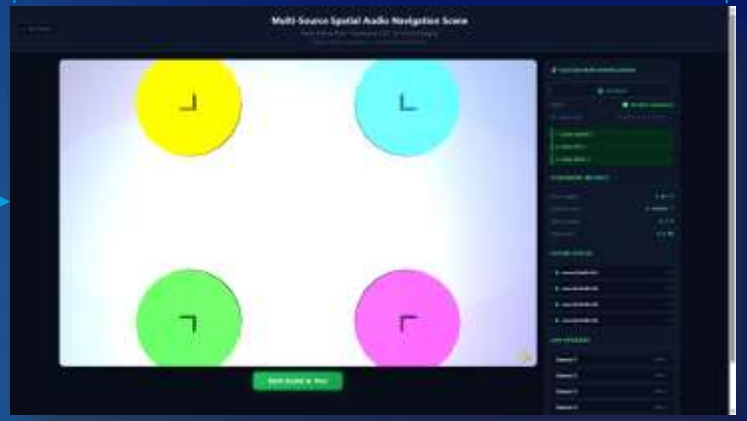
PROPOSED SYSTEM

Verification Gateway



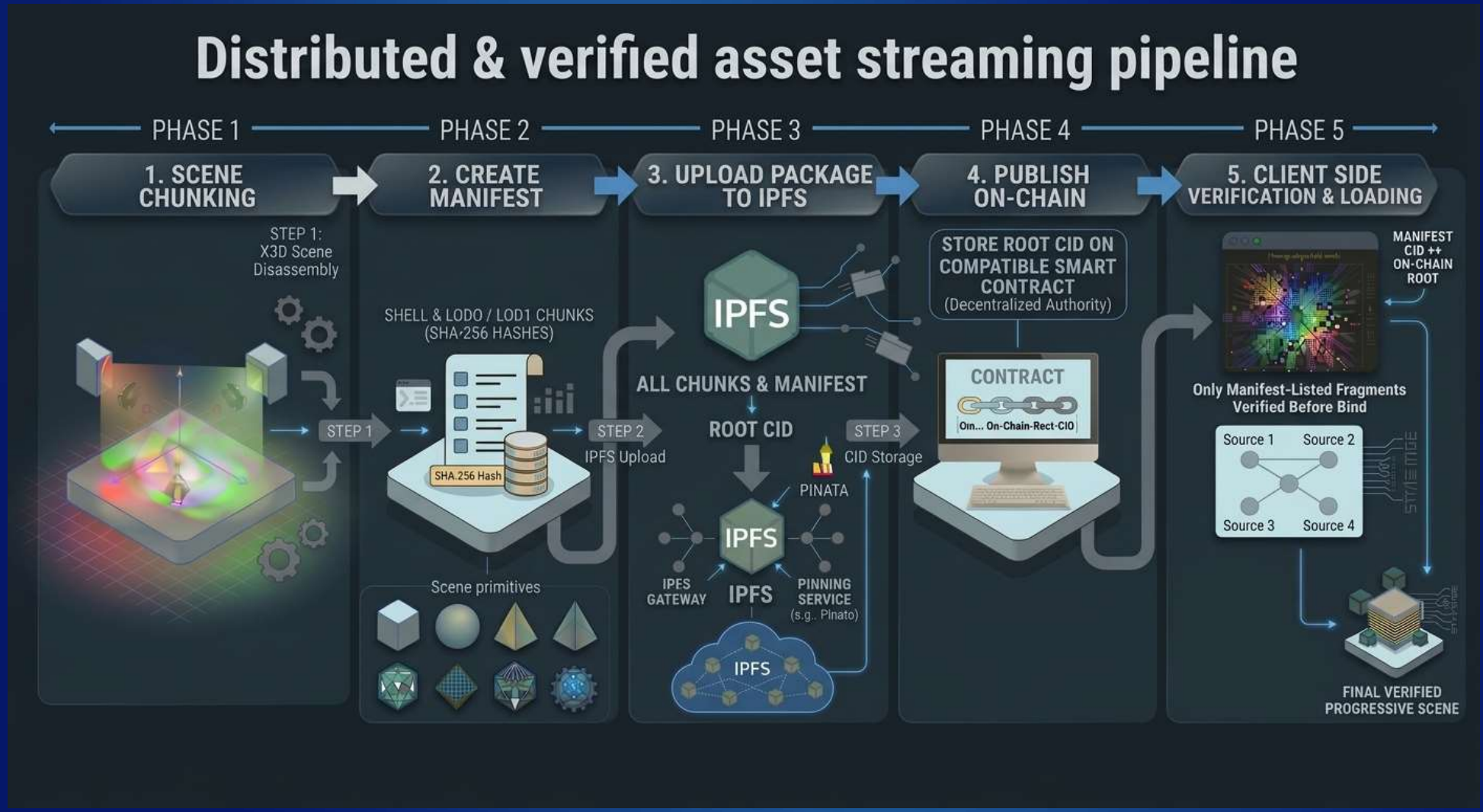
Resolve the on-chain CID, retrieve the manifest, and verify the shell before entering the scene

Verified Progressive Scene

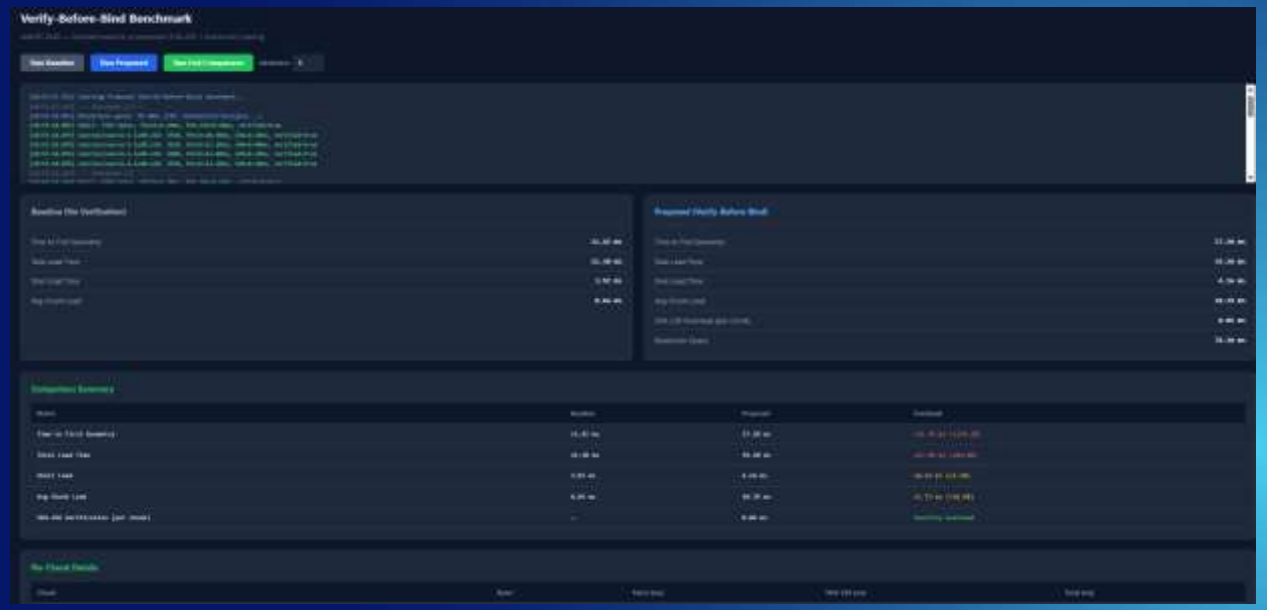


Only verified shell and LOD chunks are admitted to the live X_ITE scene graph

Prototype Implementation – Inside the Pipeline



Evaluation & Benchmark Setup



Browser-based benchmarking utility comparing baseline and verify-before-bind loading over five controlled iterations

Compared configurations:

- Baseline: direct loading
- Proposed: verify-before-bind loading
- Controlled setup

5 iterations

- Chrome 149, Windows 11
- Intel Core i3, 16 GB RAM
- Local Apache server

Measured

- Time to First Geometry
- Total Load Time
- SHA-256 per chunk
- Blockchain query latency

Purpose: isolate the performance cost introduced by verification

Results

Metric	Baseline	Verified	Overhead
Time to First Geometry	11.33 ms	25.04 ms	+13.71 ms
Total Load Time	22.44 ms	**26.74 ms**	**+4.30 ms (19.2%)**
Shell Load Time	4.66 ms	5.43 ms	+0.77 ms
Average Chunk Load	5.88 ms	8.51 ms	+2.63 ms
SHA-256 per chunk	—	**0.04 ms**	—
Blockchain Query	—	**807.38 ms**	**One-time**

✅ Positive:

- SHA-256 verification adds < 0.1 ms per chunk - cryptographic integrity is essentially free
- Total load time overhead of 19.2% is acceptable for the guarantees provided

⚠ To address:

- Blockchain query introduces 807 ms latency - however this is a one-time cost per session: after the first verification, a session token is stored in the browser and the blockchain query is bypassed for all subsequent loads within a configurable validity period

The scene is decentralised, tamper-evident, and progressively loadable - addressable by anyone holding only a contract address

Limitations

As a proof-of-concept, the current implementation intentionally prioritises feasibility over production-readiness. The following constraints define the boundaries of the evaluation.

- **Scene scale** - evaluated on a small scene with 4 audio sources and lightweight geometry; scalability to larger environments remains unverified
- **Local measurements -** assets served from a local server; IPFS gateway latency in real deployments will differ
- **Single gateway -** all fetches route through Pinata; a gateway failure blocks retrieval despite the on-chain anchor remaining valid
- **Testnet** only - Sepolia testnet; no mainnet gas cost or finality analysis
- **Manual LOD upgrade -** LOD1 triggered by user interaction only; no automatic camera-distance policy
- **Security scope -** the architecture addresses delivery integrity; malicious publishers and compromised keys are out of scope

These limitations define a clear roadmap toward a more robust and production-ready **content-addressed delivery** system for **X3D scenes**



Future Work

Three directions stand out as most impactful for advancing this work.

- **Native X3D nodes for content-addressed delivery -** just as the X3D Audio Graph brought the W3C Web Audio API declaratively into X3D, dedicated nodes for IPFS chunk loading and on-chain manifest resolution would make verifiable delivery a first-class X3D feature
- **NFT-based ownership** (ERC-721) - extend the anchor contract to encode authorship, enable provenance tracking across revisions, and support monetisation models such as tiered access and royalty distribution
- **Audio LOD -** extend the verify-before-bind pipeline to audio assets, delivering low-bitrate audio at LOD0 and high-fidelity at LOD1
- **Multi-gateway fallback and mainnet deployment -** eliminate single-provider dependency and validate economic viability
- **User study** - perceptual evaluation of verification overhead and progressive loading on user experience

Ultimate objective: production-ready, **verifiable** delivery of immersive **X3D** experiences across the open web.

Conclusions

This work set out to answer one question: can X3D spatial audio scenes be delivered over the web with integrity guarantees, without relying on any trusted server?

The answer is **yes** - and the overhead is negligible.

- Cryptographic verification adds < **0.1 ms per chunk** - integrity is essentially free
- The complete scene is addressable by a **single contract address** - no server, no prior trust relationship needed
- The X3D Audio Graph behaves **consistently across runtimes** - platform independence confirmed under X_ITE
- The approach is **extensible** - to audio LOD, NFT ownership, and native X3D nodes

This proof-of-concept establishes that decentralised, tamper-evident, progressively loadable X3D delivery is feasible and measurably efficient.



Demo & QA

Video Demo here



Multi-Source Spatial Audio Navigation Scene
Verification Gateway → Verified Progressive Scene → X_ITE

📎 Source code & prototype: github.com/efilakka/x3d-decentralized-audio-scenes

📄 Paper: *Decentralized Storage, Distribution and Verifiable Retrieval of X3D Spatial Audio Scenes* ACM Web3D 2026, Doha, Qatar



Thank You!

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