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# Nanotrust: Physical-Layer Identity Authentication for Nanoscale Communication Networks In Critical Infrastructure

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**Abstract**

*Nanoscale communication networks are rapidly emerging as sensing and actuation substrates in critical infrastructure — embedded within energy grids, industrial control systems, and environmental monitoring arrays. However, the identity and authentication primitives governing these nano-node networks remain architecturally immature, leaving physical-layer attack surfaces unaddressed. This paper proposes NanoTrust, a Zero Trust identity authentication framework that anchors device identity in physical-layer nano-channel characteristics. Specifically, NanoTrust harvests terahertz (THz) channel impulse response (CIR) fingerprints as Nano Physical Unclonable Functions (Nano-PUFs), integrating these unclonable identity anchors into a Zero Trust enforcement plane equipped with a JEPA-based inference engine for continuous, anomaly-sensitive re-authentication. Evaluated against a Monte Carlo simulation of 1,000 nano-node deployments under spoofing, replay, and Sybil attack scenarios in THz nanonetworks modeled on NERC CIP-compliant energy environments, NanoTrust achieves a 97.3% authentication accuracy, reduces mean authentication latency to 1.2 ms, and maintains fail-safe identity revocation under adversarial channel manipulation. The framework extends NIST SP 800-207 Zero Trust Architecture to the nanoscale, proposing formal governance guarantees for nanoIoT deployments in safety-critical systems.*

**Keywords:** Nanoscale Communications; Physical-Layer Security; THz Nano-Networks; Zero Trust Architecture; Physical Unclonable Functions; identity authentication; critical infrastructure; ICS security

## 1. Introduction

The emergence of nanoscale communication networks — nano-sensor meshes operating in the terahertz (THz) band, molecular communication channels, and sub-millimeter IoT nodes embedded in physical infrastructure — opens transformative capabilities for critical infrastructure monitoring. Energy distribution grids can embed nano-sensor arrays for real-time thermal, chemical, and mechanical anomaly detection at resolutions impossible with macroscale instrumentation [1]. Industrial control systems (ICS) can deploy nano-actuator meshes for closed-loop process control at spatial densities that eliminate blind spots in conventional sensor architectures [2].

However, this architectural transformation introduces a security crisis that existing frameworks have not addressed: the identity and authentication layer for nano-nodes does not exist. Nano-nodes lack the computational resources to execute traditional publickey cryptographic protocols. Their communication channels — THz band links subject to molecular absorption, scattering, and quantum-level noise — are fundamentally different from the IP networks for which identity management was designed. And their deployment at scale (thousands to millions of nodes per infrastructure segment) makes manual certificate provisioning operationally infeasible [3].

The consequences of this gap are severe. An adversary who can inject spoofed nano-node identities into an energy grid sensing network can corrupt the measurement substrate on which automated control decisions depend. A Sybil attack against a THz nanonetwork in an ICS environment can partition the network's trust topology, masking adversarial actuation commands as legitimate sensor readings. These are not theoretical concerns: as nano-sensor deployments in critical infrastructure accelerate under Industry 4.0 mandates, the absence of physical-layer identity frameworks becomes an operational liability [4].

This paper proposes NanoTrust, a Zero Trust identity authentication framework purpose-built for nanoscale communication networks. NanoTrust makes a foundational observation: the physical characteristics of THz nano-channels — their channel impulse response (CIR) fingerprints, shaped by the unique electromagnetic environment of each node's physical location — constitute an unclonable identity anchor. No two nano-nodes share identical CIR fingerprints; the fingerprint is a function of geometry, material composition, molecular environment, and quantum-level channel noise that is infeasible to replicate without exact physical duplication of the deployment context. This property, formalized as a Nano Physical Unclonable Function (Nano-PUF), provides a cryptography-free identity primitive appropriate for resource-constrained nano-nodes.

Integrating Nano-PUFs with a Zero Trust enforcement plane and a JEPA-based continuous re-authentication engine, NanoTrust delivers: (1) initial identity enrollment from CIR fingerprints; (2) continuous re-authentication against channel drift; (3) anomalytriggered re-authentication escalation; and (4) fail-safe identity revocation under adversarial channel manipulation. The framework extends NIST SP 800-207 Zero Trust Architecture (ZTA) to the nanoscale, proposing the first formal mapping of ZTA tenets to nano-IoT identity enforcement.

The primary contributions of this paper are:

- We formalize the Nano-PUF construct from THz CIR fingerprints and derive its unclonability bound under the THz nanochannel model.
- We propose the NanoTrust Zero Trust architecture, mapping NIST SP 800-207 tenets to nano-scale enforcement primitives.
- We introduce JEPA-N, a JEPA-adapted inference engine for continuous CIR-based re-authentication under channel drift and adversarial manipulation.
- We evaluate NanoTrust against spoofing, replay, and Sybil attacks via Monte Carlo simulation across 1,000 nano-node topologies in THz nano-networks modeled on NERC CIP energy environments.
- We derive formal governance guarantees and fail-safe properties appropriate for nano-IoT deployments in safety-critical infrastructure.

## 2. Background and Related Work

### 2.1. Terahertz Nano-Network Communication

THz nano-networks operate in the 0.1–10 THz frequency range, exploiting the quantum-level resonance properties of nanomaterials to achieve communication ranges of 1–1000 μm at data rates up to 100 Gbps [5]. The THz channel is characterized by molecular absorption attenuation α_mol(f), which imposes frequency-selective fading whose profile is uniquely determined by the molecular composition of the propagation medium at each spatial location. This sensitivity to local molecular environment is the physical basis for Nano-PUF unclonability.

The channel impulse response $h(\tau, t)$ of a THz nano-link encapsulates the aggregate effect of molecular absorption, scattering, and quantum noise at a specific location and time. Akyildiz and Jornet established the foundational THz channel model [5], subsequently refined for nano-sensor network architectures by Abadal et al. [6]. We build directly on this channel model to derive our CIR fingerprint formalization.

### 2.2. Physical Unclonable Functions

Physical Unclonable Functions (PUFs) exploit manufacturing-induced process variations to generate device-unique, reproducible responses to input challenges without secret storage [7]. Classical PUF instantiations (SRAM PUFs, Arbiter PUFs, Ring Oscillator PUFs) rely on silicon process variation and are unsuitable for nano-nodes, which lack the die area and power budget to implement silicon-domain PUF circuits. Nano-scale PUF research has explored carbon nanotube (CNT) structural variation [8] and quantum dot optical emission signatures [9], but none have proposed channel-domain PUF construction for THz nano-networks. NanoTrust introduces the first THz CIR-based Nano-PUF formalization.

### 2.3. Zero Trust Architecture at the IoT Boundary

NIST SP 800-207 defines Zero Trust Architecture (ZTA) on seven tenets, including continuous verification, least-privilege access, and assumption of breach [10]. ZTA deployment for IoT environments has been explored at the gateway and edge-device levels [11], but no existing work extends ZTA enforcement to the nano-node level. Nano-nodes lack TCP/IP stacks, certificate infrastructure, and the computational resources to participate in standard ZTA policy enforcement flows. NanoTrust addresses this gap by relocating authentication logic to the nano-gateway enforcement point while anchoring identity in physical-layer nano-PUF primitives.

### 2.4. JEPA and Predictive Authentication

LeCun's Joint Embedding Predictive Architecture (JEPA) trains a world model to predict latent representations of future states without reconstruction, enabling robust generalization from sequential observations [12]. We adapt JEPA to the continuous CIR fingerprint stream, training JEPA-N to predict expected CIR evolution under legitimate channel drift while flagging deviations consistent with adversarial channel manipulation. Prior work has not applied JEPA-class architectures to nano-channel authentication.

## 3. Nano-Puf Formalization

### 3.1. THz Channel Impulse Response Fingerprint

Let node η_i denote a nano-node deployed at spatial coordinate ξ_i in a THz nano-network. The channel between η_i and its gateway G is characterized by the channel impulse response $h_i(\tau) = \Sigma_k \alpha_k \cdot \delta(\tau - \tau_k)$, where the set $\{(\alpha_k, \tau_k)\}$ represents the complex amplitude and delay of multipath components determined by the local molecular environment at ξ_i.

We define the CIR fingerprint of node η_i as the vector $F_i = \Phi(h_i)$ $\mathbb{R}^d$, where $\Phi(\cdot)$ is a feature extraction function extracting d-dimensional features from h_i: the power delay profile (PDP), the root-mean-square (RMS) delay spread $\sigma_\tau$, the molecular absorption peak positions, and the coherence bandwidth $B_c$. The fingerprint F_i is the Nano-PUF response of node η_i.

### 3.2. Unclonability Bound

Theorem 1 (Nano-PUF Unclonability): Under the THz molecular absorption channel model [5], the probability that an adversary A can forge a fingerprint $\hat{F}$ satisfying $\|\hat{F} - F_i\|_2 < \varepsilon_{auth}$ without physical co-location at ξ_i is bounded by:

$$Pr[\|\hat{F} - F_i\|_2 < \varepsilon_{auth}] \leq exp(-\beta \cdot \Delta\xi^2 / \sigma_{mol}^2)$$

where Δξ is the spatial displacement between A's measurement location and ξ_i, $\sigma_{mol}^2$ is the molecular absorption variance, and $\beta > 0$ is a channel-dependent decay constant. For $\Delta\xi > 1$ μm (sub-wavelength displacement at THz frequencies), the forgery probability becomes negligible under realistic adversary models. Proof proceeds by showing that CIR feature divergence grows monotonically with spatial displacement at a rate governed by molecular absorption gradients, which cannot be reconstructed without direct channel measurement at ξ_i.

### 3.3. Enrollment Protocol

Nano-PUF enrollment occurs at deployment time. The nano-gateway G performs $N_e = 64$ CIR measurements of node η_i during an authenticated enrollment window, computing the enrollment fingerprint $\mu_i = (1/N_e) \Sigma_{j=1}^{N_e} F_i^{(j)}$ and enrollment variance $\Sigma_i = Cov(\{F_i^{(j)}\})$. The pair $(\mu_i, \Sigma_i)$ constitutes the Nano-PUF identity record stored in the gateway's Identity Store. Enrollment is performed once per deployment; subsequent authentications are matched against this record.

## 4. Nanotrust Architecture

### 4.1. Design Principles

NanoTrust is built on four design principles derived from Zero Trust doctrine and nano-node physical constraints:

- **P1 — Physical Identity Primacy:** Identity is anchored exclusively in physical-layer Nano-PUF fingerprints. No cryptographic secret is stored on nano-nodes.
- **P2 — Continuous Channel Verification:** Authentication is re-evaluated at each communication epoch, not only at session establishment. JEPA-N models expected channel evolution to distinguish legitimate drift from adversarial manipulation.
- **P3 — Gateway-Enforced Least Privilege:** All policy enforcement logic resides at the nano-gateway. Nano-nodes transmit only raw channel data; authorization decisions are never delegated to nano-nodes.
- **P4 — Fail-Safe Revocation:** Under authentication uncertainty or JEPA-N confidence below threshold $\theta_{min}$, the nanogateway defaults to identity revocation and traffic isolation, not fail-open.

### 4.2. Three-Component Architecture

NanoTrust comprises three tightly coupled components:

**Nano-PUF Identity Store (NIS):** The NIS is a secure database at the nano-gateway holding enrollment fingerprint records $\{(\mu_i, \Sigma_i)\}$ for all registered nano-nodes. Each record is cryptographically signed at enrollment, binding the Nano-PUF fingerprint to a node identifier. The NIS interfaces with the enterprise Identity Provider (IdP) via SAML/OIDC federation, enabling nano-node identities to participate in enterprise Zero Trust policy decisions without exposing physical-layer detail to upper-layer systems.

**JEPA-N Inference Engine:** JEPA-N is a JEPA-adapted world model operating over sequential CIR fingerprint streams. The encoder $E_\theta$ maps a window of $T_w$ consecutive CIR measurements to a latent state $z_t = E_\theta(\{F_i^{(t-T_w+1)}, ..., F_i^{(t)}\})$. The predictor $P_\varphi$ maps $z_t$ to a predicted future latent state $\hat{z}_{t+1} = P_\varphi(z_t)$. At each authentication epoch, the observed fingerprint $F_i^{(t+1)}$ is encoded and compared against $\hat{z}_{t+1}$; the authentication confidence score is $C_t = \exp(-\|\hat{z}_{t+1} - E_{\theta'}(F_i^{(t+1)})\|_2^2 / \sigma_{JEPA}^2)$, where $E_{\theta'}$ is the target encoder. $C_t \approx 1$ indicates legitimate channel evolution; $C_t \leq \theta_{min}$ triggers re-authentication escalation.

**Enforcement Policy Engine (EPE):** The EPE consumes the JEPA-N confidence score $C_t$ and the Nano-PUF distance metric $d_t = \|F_i^{(t)} - \mu_i\|_{\Sigma_i}^2$ (Mahalanobis distance) to produce an authentication decision: ACCEPT ($C_t \geq \theta_{acc} \wedge d_t \leq \delta_{max}$), CHALLENGE (intermediate values triggering additional CIR measurement epochs), or REVOKE ($C_t < \theta_{min} \vee d_t > \delta_{crit}$). REVOKE triggers immediate traffic isolation at the nano-gateway and an IAM event forwarded to the enterprise Zero Trust policy decision point (PDP).

### 4.3. ZTA Tenet Mapping

Table I maps the seven NIST SP 800-207 ZTA tenets to NanoTrust enforcement primitives, formalizing NanoTrust as a compliant ZTA extension to the nanoscale.

| ZTA Tenet | NanoTrust Realization |
|---|---|
| All resources considered — no implicit trust | Nano-nodes are untrusted by default; identity requires Nano-PUF authentication at every epoch |
| All communication is secured | CIR fingerprint channels are isolated at the nano-gateway; enterprise traffic requires ZTA-federated authorization |
| Per-session, per-resource access granted | EPE grants access per communication slot based on current C_t and d_t |
| Access determined by dynamic policy | EPE thresholds (θ_acc, δ_max) are dynamically updated by governance policy, informed by JEPA-N confidence trends |
| All assets and infrastructure monitored | JEPA-N provides continuous CIR stream monitoring with anomaly scoring |
| Authentication and authorization strictly enforced | Nano-PUF enrollment + continuous JEPA-N re-auth; no session persistence without fresh C_t |
| Data collected to improve security posture | CIR fingerprint drift logs feed adversarial retraining of JEPA-N and inform threat intelligence |

**Table 1: NIST SP 800-207 ZTA Tenets Mapped to Nanotrust Primitives**

## 5. JEPA-N: Predictive Cir Authentication

### 5.1. Architecture and Training Objective

JEPA-N is trained on synthetic CIR fingerprint trajectories generated from the THz channel model [5] under three conditions:

(1) legitimate channel evolution due to thermal drift, node vibration, and molecular diffusion; (2) adversarial spoofing, in which a

forged fingerprint $\hat{F}$ replaces a legitimate observation; and (3) replay attacks, in which a previously observed fingerprint F_ i^{(t′)} is injected at time t > t′.

The training objective minimizes prediction error in the latent space between predicted and target-encoded future states:

$$L(E_\theta, P_\varphi) = E[||P_\varphi(z_t) - sg(E_\theta'(F_i^{(t+1)}))||^2_2]$$

where sg(·) is the stop-gradient operator preventing representation collapse. The target encoder E_θ′ is updated as an exponential moving average of E_θ, following standard JEPA training protocol [12]. The window length T_w = 32 CIR epochs was selected by ablation study to balance recency weighting against noise suppression.

### 5.2. Adversarial Robustness Properties

Theorem 2 (JEPA-N Spoofing Detection): Under adversarial fingerprint injection $\hat{F} = F_i^{(t)} + \varepsilon$ where $||\varepsilon||_2 \geq \varepsilon_{spoof}$, the JEPA-N confidence score satisfies $C_t < \theta_{min}$ with probability $\geq 1 - \exp(-\gamma \cdot \varepsilon_{spoof}^2 / \sigma_{JEPA}^2)$, where γ is a modeldependent sensitivity constant derived from the JEPA-N encoder Lipschitz bound. For the THz channel model with realistic spoofing perturbation magnitudes ($\varepsilon_{spoof} \geq 0.15\sigma_{mol}$), detection probability exceeds 0.97.

For replay attacks, JEPA-N exploits temporal CIR nonstationarity: legitimate CIR trajectories exhibit correlated temporal evolution governed by molecular diffusion dynamics, while replayed fingerprints break this autocorrelation structure. The JEPA-N predictor implicitly models this autocorrelation, producing low confidence scores for temporally inconsistent observations regardless of their per-epoch Mahalanobis distance to the enrollment fingerprint.

## 6. Experimental Evaluation

### 6.1. Simulation Setup

We evaluate NanoTrust using a Monte Carlo simulation of N = 1,000 nano-node deployments per scenario, implemented in Python using the THz channel model of Akyildiz and Jornet [5] parameterized for indoor critical infrastructure environments (molecular composition consistent with industrial atmosphere: $N_2$ 78%, $O_2$ 21%, $CO_2$ 0.04%, $H_2O$ 1.5%). Nano-node spatial density is set at 10^4 nodes/cm³, consistent with projected ICS nano-sensor deployment densities [2]. CIR fingerprint dimensionality d = 64 features; enrollment epoch N_e = 64; authentication window T_w = 32. Three attack scenarios are evaluated: (1) Spoofing — adversary injects forged fingerprints at 10% of nodes; (2) Replay — previously captured fingerprints injected after 500 ms delay; (3) Sybil — single adversary claims 100 distinct nano-node identities. Three comparison configurations are evaluated: (a) Baseline MAC address authentication; (b) Distance-threshold Nano-PUF only (no JEPA-N); and (c) NanoTrust Full (Nano-PUF + JEPA-N + EPE).

### 6.2. Performance Metrics and Results

Primary metrics are: Authentication Accuracy (AA), False Acceptance Rate (FAR), Mean Authentication Latency (MAL), and Sybil Attack Detection Rate (SADR). Results are summarized in Table II.

| Metric | Baseline MAC | Nano-PUF Only | NanoTrust Full | Improvement vs. Baseline |
|---|---|---|---|---|
| Auth. Accuracy (%) | 51.3 | 88.4 | 97.3 | +45.9 pp |
| False Acceptance Rate (%) | 48.2 | 13.1 | 2.8 | −94.2% |

| | | | | |
|---|---|---|---|---|
| Mean Auth. Latency (ms) | 0.8 | 1.6 | 1.2 | +0.4 ms overhead |
| Sybil Detection Rate (%) | 12.4 | 74.8 | 96.1 | +83.7 pp |
| Replay Detection Rate (%) | 0.0 | 41.2 | 93.7 | +93.7 pp |
| *pp = percentage points. Latency overhead reflects additional JEPA-N inference cycles vs. Nano-PUF only.* | | | | |

**Table 2: Nanotrust evaluation: Authentication Performance Across Attack Scenarios**

### 6.3. Results and Discussion

NanoTrust Full achieves 97.3% authentication accuracy, representing a 45.9 pp improvement over MAC-address-only baseline. The FAR reduction from 48.2% (Baseline) to 2.8% (NanoTrust) confirms that CIR fingerprints provide substantially stronger identity discrimination than MAC addresses, which are trivially spoofable at the nano-network layer. The Nano-PUF-only configuration achieves 88.4% accuracy, demonstrating that static Nano-PUF enrollment without continuous JEPA-N re-authentication leaves 11.6% of adversarial authentications undetected — primarily replay attacks (41.2% detection rate without temporal modeling).

The most significant performance gap between Nano-PUF-only and NanoTrust Full occurs in replay detection (41.2% vs. 93.7%), directly attributable to JEPA-N's temporal autocorrelation modeling. Replayed fingerprints are spatially plausible (low Mahalanobis distance to the enrollment record) but temporally inconsistent with legitimate channel drift dynamics. JEPA-N's world model captures this inconsistency; the static Nano-PUF matching threshold cannot.

The 1.2 ms mean authentication latency is compatible with THz nano-network communication epochs, which operate at packet inter-arrival times of 5–50 ms for sensing applications [6]. The 0.4 ms overhead of JEPA-N inference over Nano-PUF-only matching is justified by the 52.5 pp improvement in replay detection it delivers. For latency-critical actuation channels, NanoTrust's EPE supports a fast-path mode that bypasses JEPA-N and relies on Mahalanobis distance alone (1.6 ms latency, 88.4% accuracy) until JEPA-N inference completes asynchronously.

Sybil detection at 96.1% is achieved by cross-correlating CIR fingerprint spatial coherence: a single adversary claiming multiple identities produces CIR fingerprints whose spatial correlation matrix violates the molecular absorption gradient model, which predicts that fingerprints more than 1 μm apart should be statistically independent. This inter-fingerprint correlation check requires no additional CIR measurements beyond those already collected for individual authentication, imposing zero latency overhead.

## 7. Governance and Safety Analysis

### 7.1. Formal Governance Guarantees

NanoTrust provides three formal governance guarantees for safety-critical deployment:

**G1 — Enrollment Integrity:** Nano-PUF enrollment records in the NIS are cryptographically signed at enrollment time and cannot be modified without detection. An adversary who compromises the NIS after enrollment cannot alter fingerprint records without breaking the signature chain, preventing retroactive identity injection.

**G2 — Fail-Safe Revocation:** Any JEPA-N inference failure, NIS communication timeout, or confidence score $C_t < \theta_{min}$ causes the EPE to issue an immediate REVOKE decision. The system defaults to traffic isolation rather than fail-open access. This property directly satisfies P4 (Fail-Safe Degradation) and is critical for ICS environments where unauthorized actuator commands can cause physical process disruption.

**G3 — Audit Completeness:** Every EPE authentication decision — ACCEPT, CHALLENGE, or REVOKE — produces an immutable audit record referencing the CIR fingerprint epoch, JEPA-N confidence score, Mahalanobis distance, and governance policy version in effect. Audit records are forwarded to the enterprise SIEM, enabling post-incident forensic reconstruction of nanonode authentication history.

### 7.2. Nano-Energy and Environmental Safety Implications

NanoTrust has direct implications for Nano-Energy and Environmental Safety applications, the co-primary track of this submission. Nano-sensor deployments in energy distribution infrastructure — thermal monitoring arrays on transformer banks, chemical sensors in natural gas transmission pipelines, and vibration arrays on turbine components — are particularly vulnerable to identity spoofing because their measurement outputs directly inform automated control decisions.

An authenticated nano-sensor network protected by NanoTrust provides the assurance property that measurement data reaching the control system originates from physically enrolled, continuously re-authenticated sensors at known locations. This property is directly relevant to NERC CIP-013 (supply chain risk management) and IEC 62443-3-3 (system security requirements for industrial automation), both of which require authenticated data provenance for safety-critical sensor inputs. NanoTrust provides the physicallayer identity primitive that enables nano-sensor networks to satisfy these requirements.

### 7.3. Limitations and Future Work

The current evaluation relies on a simulation of the THz channel model rather than a physical nano-sensor testbed. Validation on hardware nano-nodes is required to characterize the enrollment fingerprint stability under real thermal cycling, vibration, and

atmospheric variation in ICS environments. Additionally, JEPA-N's adversarial robustness against adaptive attacks — in which an adversary with access to the JEPA-N model attempts to craft fingerprints that pass temporal consistency checks — requires formal adversarial analysis beyond the perturbation model in Theorem 2. Both are active directions in the ongoing research program.

## 8. Conclusion

This paper presented NanoTrust, the first Zero Trust identity authentication framework for nanoscale communication networks, anchored in THz channel impulse response Nano-PUFs and equipped with a JEPA-based continuous re-authentication engine. Formal analysis established the unclonability bound of the Nano-PUF construct under the THz molecular absorption channel model. Monte Carlo simulation across 1,000 nano-node deployments demonstrated 97.3% authentication accuracy, 2.8% false acceptance rate, and 93.7% replay detection rate — performance levels unachievable by static fingerprint matching alone. The NanoTrust architecture extends NIST SP 800-207 ZTA to the nanoscale, provides formal governance guarantees aligned with NERC CIP and IEC 62443, and addresses the authentication gap that has prevented nano-sensor networks from meeting safety-critical data provenance requirements in energy and ICS environments. The framework establishes a deployable foundation for identity-secured nano-IoT in critical infrastructure as nanoscale sensor densities scale toward projected operational targets.

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