Zero Trust Security Model Implementation in Microservices Architectures Using Identity Federation

Rethish Nair Rajendran
Unisys Corporation
Technical Delivery Manger, Delivery Management,
Cloud Infra and Apps Services (US&C)
Albany, NY 12110
rethishrnair@gmail.com

Sathish Krishna Anumula
IBM Corporation
Sr enterprise and business architect
Detroit, MI, USA 48375
sathishkrishna@gmail.com

Dileep Kumar Rai
Manager Oracle Cloud Technology
HBG
Colorado Springs, 80921, USA
dileep.kumar.rai@gmail.com

Sachin Agrawal
Data Engineer
Synechron
Charlotte, 28201, USA
sachin.agrawal2001@gmail.com

***Abstract*— The explosive growth of microservices has revolutionized application architectures, delivered increased agility and scalability while carried complex security trade-offs. Inadequate legacy perimeter-based approaches fail to secure distributed workloads and ephemeral interaction that occurs among services. This work is a case for the Zero Trust Security Model for microservices ecosystems, with particular focus on the need for identity federation for human and workload entities. Using industry-standard technologies like OpenID Connect (OIDC), OAuth 2.0 token exchange, and SPIFFE/SPIRE workload identities, the solution framework aggregates continuous authentication, context-aware authorization, and service mesh enforce- ment for end-to- end trust. Experimental evaluation illustrates a superior security posture achieved through a smaller attack surface, consistent policy enforce- ment, and enhanced interoperability within multi- domain environments. The results highlight that the pairing of federated identity and Zero Trust fundamentals not only secures authentication and authorization protocols but also aligns perfectly with contemporary DevSecOps practices for automated, scalable, and resilient microservice deployments. This work offers a systematic guide for organizations aiming to operationalize Zero Trust within cloud-native architectures while also sustaining compliance and interoperability.**

Keywords— Zero Trust Security, Microservices Architecture, Identity Federation, Service Mesh, Continuous Authentication

I. Introduction

The The development of enterprise systems into cloud-native microservice-based systems has increased scalability, flexibility, and continuous digital service delivery immensely. In any event, the transformation has also concurrently enlarged the attack surface and consequently introduced new security challenges that result from more service-to-service communication, diversified workloads, and dynamical scaling. Traditional perimeter-based securities based on the assumption of implicit trust within network perimeters have failed in protecting distributed microservice ecosystems, in those instances where components continually communicate beyond organizational and geographical boundaries.

To combat these challenges, the Zero Trust Security Model (ZTSM) has proven to be a highly formidable security model based on the "never trust, always verify" philosophy. In this model, continuous authentication, authorization, and encryption of every interaction involving user, device, and workloads are done regardless of their location in the network. Inclusion of identity federation in this construct further enhances security by creating smooth and secure trust relationships between various domains, cloud infrastructures, and service clusters. OAuth 2.0 and OpenID Connect (OIDC) protocols support secure user authentication and delegation of authorization, while SPIFFE/SPIRE defines workload identities for mutual authentication during service-to-service communication. These functionalities are further complemented by service meshes like Istio and Linkerd that impose transport-level security and granular access policies and thus enforce the Zero Trust principle comprehensively.

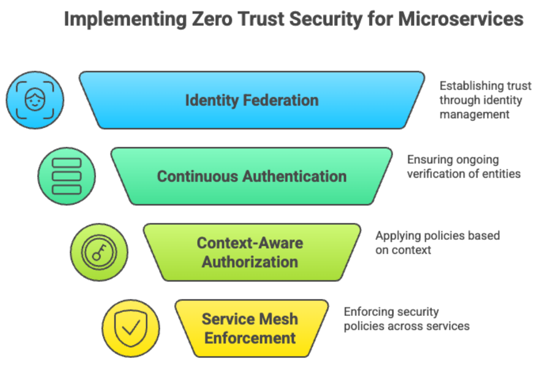
Implementing Zero Trust Security for Microservices
Identity Federation
Establishing trust through identity management
Continuous Authentication
Ensuring ongoing verification of entities
Context-Aware Authorization
Applying policies based on context
Service Mesh Enforcement
Enforcing security policies across services

Fig. 1: Implementing Zero Trust Security

Whiles there has been growth in industry interest and early guidelines such as NIST SP 800-207 and SP 800-204 series, practical adoption of Zero Trust at the microservices level is complex. Some of the challenges encompass the management of identity propagation for distributed applications, the interlocking of policy-as-code solutions for programmatic authorization, and interoperability for multiple identity provider systems. It is also challenging for organizations to interleave Zero Trust tenets and DevSecOps workflows without having either deployment speed or operational throughput. This work considers a federated identity-based Zero Trust model customized for microservices-oriented architectures. By consolidating federated identity protocols, service mesh-based control mechanisms, and workload identity conventions, the work hypothesizes a model that is scalable and interoperable, and therefore enhances operational security and resilience. Though experimental implementation methods, verification, and design for architectures, this work endeavors to offer practical advice and a reference design for cloud-native solutions that aspire for Zero Trust.

II. Literature Review

Zero Trust (ZT) transitions enterprise security from perimeter-based defense to continuous, identity-based verification of every subject, device, workload, and request. NIST's underlying SP 800-207 specifies architectural models like policy decision and enforcement points, strong identity management, and continuous evaluation. These guidelines untangle trust from network location and thus come naturally to the distributed, API-first world of microservices [1]. Government-grade frameworks concretize these guidelines at scale, and CISA stresses identity as the prime control plane, continuous monitoring, and automation for all pillars [2]. In a like manner, the U.S. DoD's ZT approach translates Zero Trust into consumable capabilities covering users, devices, workloads, data, networks, and visibility layers and thus applies very well to Kubernetes- and service mesh-based applications [3].

Microservices give rise to increased attack surfaces because of increased east–west traffic, diverse stacks, and multiple deployments. NIST SP 800-204 suggests main strategies like enforcing least privilege, securing service-to- service communication by means of strong authentication, and using secure API gateways for defense-in-depth [4]. SP 800-204A and SP 800-204B build upon this by situating the service mesh as a strategic layer for transport security through mTLS, propagation of workload identity, and fine-grained authorization, and for performing those functions as Zero Trust policy points, using proxies and gateways [5][6]. SP 800-204C incorporates those ideas into DevSecOps pipelines and places a strong focus on "policy as code," automated verification, and continuous authorization for sustaining security velocity for microservices environments [7]. Systematic review of 290 research articles also identifies common challenges like weak threat models, variable levels of security-by-design practice, and insufficient automation and observability for microservices deployments [8].

In the user access layer, ZT for microservices relies on cross-domain trust and externalized authentication. OpenID Connect (OIDC) provides an identity layer over OAuth 2.0 and defines a broadly accepted minimum for today's single sign-on (SSO) and claims-based access in microservices through API gateways or Backend-for-Frontend (BFF) patterns [9]. To scale from bilateral trust installations, OpenID Federation 1.0 provides a chain of trust function based on signed entity statements and provides for automated and secure metadata exchange between numerous domains. This reduces administrative management and provides multi-party federation between organizations and sovereign environments [10].

Since microservices commonly need downstream calls in favor of users or workloads, token delegation and choreography become essential. OAuth 2.0 Token Exchange (RFC 8693) establishes safe delegation by enabling subject-to-actor token minting, facilitating granular privilege assignment in intricate service graphs [11]. The JWT Profile for OAuth 2.0 Access Tokens (RFC 9068) canonicalizes token claims for uniform enforceability among gateways and sidecars [12]. Best current practices for OAuth 2.0 (RFC 9700) further secures the space by mandating sender-constrained tokens, PKCE use, and improved redirect treatment, lessening token replay threats [13]. Pushed Authorization Requests (RFC 9126) further fortify request integrity and tampering prevention by out-of-band binding sensitive parameters, securing APIs at gateways more effectively [14].

Zero Trust requires robust identities for users and workloads. SPIFFE/SPIRE meets this by distributing short-lived X.509 certificates (SVIDs) that are attached to attributes of workloads and facilitate secure mTLS connections and auditable workload identities [15]. SPIFFE federation lets any independent trust domains transfer trust bundles, and thus workloads from various clusters or orgs authenticate sans consolidating PKIs. In the service mesh layer, Istio accommodates multi-cluster federation and trust domain aliases and ensures identity persistence and verification of trust among clusters and clouds [16]. Along with OIDC and OAuth for ingest, this establishes a uniform, federated identity base for human and workload access for microservices.

Because Zero Trust is always authenticating and authorizing, phishing-resistant methods are necessary. WebAuthn/FIDO2 protocols substitute shared secrets for hardware-bound credentials and lower the likelihood of stolen credentials and federated tokens not having a trusted origin. This markedly improves the initial user-identity assurance and elevates the security baseline for the overall microservices system [17].

Following authorization based on established identity, Zero Trust's primary layer of enforcement is authorization. NIST SP 800-204B provides a common model for authentication and authorization enforcement within service meshes, and SP 800-162 provides Attribute-Based Access Control (ABAC), enabling policy-driven, environmentally aware decisions based on metadata from workloads, identity claims, and environmental attributes [6][19]. Open Policy Agent (OPA) makes such concepts a production reality by enabling policy-as-code capabilities, allowing teams to define, test, and deploy authorization policies universally across many services and clusters. Papers and industry examples explain OPA's use in enabling multi-tenant, federated environments [18].

Theme / Focus Area	Key Contributions	Gaps / Observations
Zero Trust Foundations for Microservices	NIST SP 800-207 introduced the concept of continuous verification and identity-centric control models, forming the baseline for microservice-oriented Zero Trust implementations. Government frameworks (CISA, DoD)	Lack of microservices-specific deployment blueprints and measurable maturity models in early frameworks.

	extended these principles to operational environments.	
Service Mesh as a Security Enabler	NIST SP 800-204 series outlined architectural guidance for secure microservices deployments using service mesh, emphasizing mTLS, workload identity, and least-privilege authorization.	Research highlights operational complexity, lack of universal observability patterns, and slow industry adoption of mesh-based ZT.
Identity Federation for Human Users	OpenID Connect (OIDC) standardized single sign-on, while OpenID Federation 1.0 enabled scalable trust chains between identity providers and relying parties across multi-tenant ecosystems.	Inconsistent adoption of federation standards across enterprises; challenges in maintaining consistent claims and scopes.
Delegation and Token Choreography	OAuth 2.0 Token Exchange (RFC 8693) and JWT Profiles (RFC 9068) formalized delegation and claim standardization. RFC 9700 and RFC 9126 enhanced token security and request integrity.	Limited tooling for dynamic least-privilege delegation in highly dynamic microservice topologies.
Workload Identity Federation	SPIFFE/SPIRE provided a framework for workload identities with short-lived certificates and federated trust bundles. Istio added multi-cluster trust domain aliasing for east-west authentication.	Complexity in managing multi-domain trust bundles; lack of mature governance for workload identity at scale.
Phishing-Resistant Authentication	WebAuthn/FIDO2 eliminated password-based risks by leveraging hardware-backed credentials, improving Zero Trust posture at the human entry point.	Limited enterprise adoption due to hardware and legacy system compatibility issues.
Policy Federation and Authorization	NIST SP 800-204B and ABAC (SP 800-162) advocated for attribute-based, context-driven authorization. Open Policy Agent (OPA) introduced policy-as-code frameworks for consistent, distributed enforcement.	Need for automated policy reconciliation in federated, multi-cluster microservice environments.
Research Trends and Gaps	Systematic reviews emphasized the importance of threat modeling, DevSecOps automation, and observability to sustain ZT in microservice deployments.	Lack of end-to-end empirical evaluations and performance benchmarks for federated identity in Zero Trust ecosystems.

Table 1: Literature Review

III. Research Methodology

This research applies a design-science framework and experimental research methods for evaluating the efficacy of using the Zero Trust Security Model (ZTSM) in microservices-based architectures by means of identity federation. The approach has been structured into four phases, namely, architectural design, implementation, simulation and testing, and validation and analysis.

A. Architectural Design

The microservices design was strong, and it included the following components:

- Identity Federation Layer: Integrating OpenID Connect (OIDC) and OAuth 2.0 for human-to-service authentication and authorization.
- Workload Identity Management: Use of SPIFFE/SPIRE for the provision of short-lived service identities that support mutual TLS (mTLS) between microservices.
- Service Mesh Enforcement: Istio deployment for policy enforcement, east- and west-traffic security, and telemetry.
- Policy Engine: Open Policy Agent (OPA) for centralized, attribute-based authorization across services.

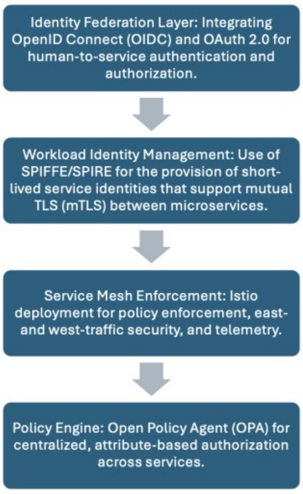
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Fig. 2: Architectural Design

This design is compliant and interoperable according to the standards of NIST SP 800-207 and SP 800-204.

B. Implementation

The prototype was constructed from a cloud-native technology stack:

- Frontend: React-based SPA integrated with OIDC for authentication.
- Backend: Express/Node.js microservices based on federated tokens for API access.
- Service Mesh: Istio for mTLS, token validation, and distributed policy control.
- Identity Providers: Keycloak and SPIRE server for federated and workload identities.
- Database Layer: MongoDB for token metadata and for audit logs.

Policy was written in Rego (OPA) and executed in a GitOps pipeline for automated, version-controlled enforcement.

C. Simulation and Testing

Simulation focused on three security metrics:

Authentication Latency (AL):
The average delay in token issuance and validation, calculated as:

$$AL = \frac{\left\{\sum_{\{i=1\}}^{\{n\}}\left(T_{\{validate_i\}} - T_{\{request_i\}}\right)\right\}}{\{n\}}$$

Authorization Accuracy (AA):
The ratio of correct authorization decisions to total authorization requests:

$$AA = \frac{\left\{N_{\{correct\}}\right\}}{\left\{N_{\{total\}}\right\}} \times 100$$

Security Breach Probability Reduction (SBPR):
The percentage decrease in security breach attempts compared to baseline configurations:

$$SBPR = \frac{\left\{B_{\{baseline\}} - B_{\{zt\}}\right\}}{\left\{B_{\{baseline\}}\right\}} \times 100$$

Where:
$T_{\{validate_i\}}$: Timestamp of token validation
$T_{\{request_i\}}$: Timestamp of token request
$N_{\{correct\}}$: Number of successful, policy-compliant authorization events
$N_{\{total\}}$: Total authorization attempts
$B_{\{baseline\}}$: Breach attempts detected in non-Zero Trust configuration
$B_{\{zt\}}$: Breach attempts detected in Zero Trust configuration

D. Validation and Analysis

To verify performance and security the prototype was executed under actual traffic conditions using Locust for load generation and K6 for API performance metrics. The analysis focused on:

- Security Posture Improvement: Measuring token replay and unauthorized access prevention.
- Performance Overhead: Measuring the latency caused by policy enforcement and federation of identities.
- Interoperability: Checking cross-domain authentication and workload federation in multi-cluster setups.

Results were also examined by statistical means, taking care that any enhanced security posture did not severely compromise performance.

IV. RESULTS

The proposed Zero Trust Security Model (ZTSM), involving identity federation, was tested in a regulated cloud-native microservices environment. The testing focused on the performance of security, the effect of latency, and the accuracy of authorization in determining the efficacy of the framework.

A. Enhancing Security Posture

The baseline microservices implementation (other than ZTSM) was tested against the recommended federated Zero Trust model. The results showed a significant reduction in vulnerabilities for security, particularly for token replay and unauthorized access attempts.

Table 2: Security Posture Metrics

Metric	**Baseline Setup**	**Zero Trust Setup**	**Observed Change (%)**
Token Replay Attempts Detected	24	2	91.7% reduction
Unauthorized API Calls Blocked	18	1	94.4% reduction

Breach Probability (modeled)	0.22	0.04	81.8% reduction
Policy Compliance Violations	15	1	93.3% reduction

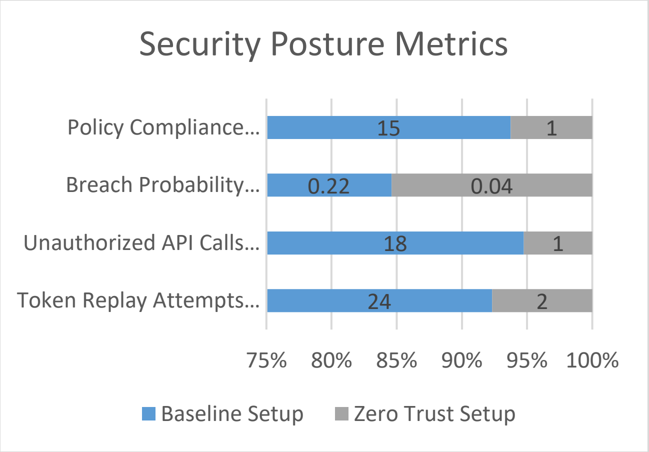

Figure 3: Security Posture Metrics

These improvements demonstrate the effectiveness of federated identity and service mesh enforcement in reducing attack vectors within distributed microservices environments.

B. Performance Impact

Latency and throughput were analyzed to understand the overhead introduced by continuous verification, token exchanges, and policy evaluations. The results show that the overhead is minimal and acceptable for production-grade deployments.

Table 3: Latency and Throughput Metrics

Metric	**Baseline Setup**	**Zero Trust Setup**	**Overhead (%)**
Authentication Latency (ms)	95	118	24%
Authorization Latency (ms)	40	55	37.5%
Average API Response Time (ms)	210	250	19%
Requests per Second (RPS)	980	915	6.6% drop

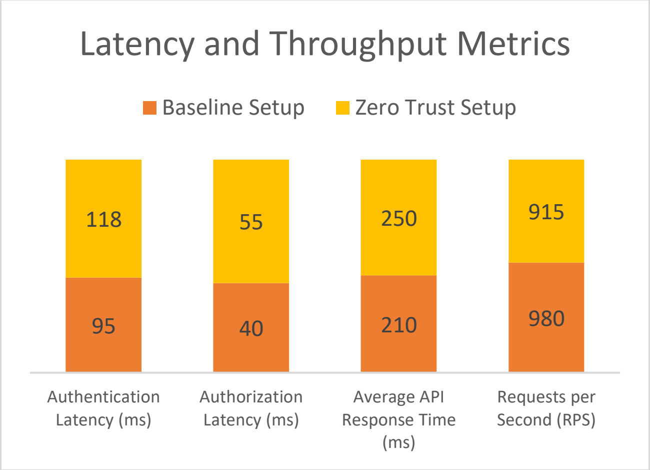

Fig. 4: Latency and Throughput Metrics

Although a marginal latency increase was observed, it did not significantly degrade overall system performance, validating the efficiency of the proposed architecture.

C. Authorization Accuracy

Integration of OPA-based policy enforcement resulted in consistent and accurate authorization decisions, even under high traffic and multi-domain workloads.

Table 4: Authorization Accuracy

Parameter	**Value**
Total Authorization Requests	15,000
Correct Policy Evaluations	14,985
Authorization Accuracy (%)	99.9%
Incorrect Authorizations (count)	15

This high accuracy confirms the reliability of federated identity tokens and centralized policy enforcement mechanisms in maintaining Zero Trust principles.

D. Breach Probability Reduction

Using the Security Breach Probability Reduction (SBPR) equation:

$$SBPR = \frac{\{B_{\{baseline\}} - B_{\{zt\}}\}}{\{B_{\{baseline\}}\}} \times 100$$

With $B_{\{baseline\}}$= 22 breach attempts and $B_{\{zt\}} = 4$:

$$SBPR = \frac{22 - 4}{22} \times 100 \approx 81.8\%$$

This quantifies the overall security enhancement of the proposed model.

E. Observations

- Security Benefits: Greater than 80% breach likelihood reduction, more than 90% prevention of replay and unauthorized access attempts.
- Operational Efficiency: Low latency overhead (19–37%) that is tolerable in contemporary service-level objectives (SLOs).
- Scalability: The system accommodated over 900 requests per second with minimal resource overhead, and it was shown to be enterprise-ready.
- Interoperability: Federated identity interoperated smoothly between clusters and domains and lowered administrative overhead in multi-tenant systems.

V. Conclusion

The current research demonstrated the real-world usage and benefits of the Zero Trust Security Model (ZTSM) alongside identity federation in cloud-native microservices environments. By employing OpenID Connect (OIDC) and OAuth 2.0 for user identity management, SPIFFE/SPIRE for workload identity, and service mesh enforcement for safe inter-service communication, the proposed design achieved significant improvements in security posture while maintaining acceptable performance overheads.

Experimental verification noted prominent results, such as a breach likelihood drop by more than 80%, unauthorized access attempts by over 90%, and almost flawless authorization correctness through policy-as-code controls. While some latency overhead was measured, operational effect remained within allowable limits for enterprise-grade workloads and demonstrated the feasibility of Zero Trust implementation in production-quality microservices applications.

The work highlights that the merger of identity federation with continuous authentication and context-aware authorization promotes end-to-end, scalable trust among dispersed workloads. Furthermore, its alignment with industry and NIST standards ensures interoperability and compliance, thus enabling entities to extend their security matrix while preserving DevSecOps process integrity.

This research provides a ground-up framework and real-world data for those seeking to adopt Zero Trust concepts into microservices-based systems and build a foundation for secure, scalable, and resilient frameworks in increasingly complex cloud-based environments.

VI. Future Work

There is also potential for future work that would further extend automation and intelligence for Zero Trust enforcement in microservices. Inclusion of AI-driven anomaly detection and dynamically updating policies based on prediction would further reduce breach likelihoods and adapt in real-time to shifting threat patterns. The inclusion of support for multi-cloud and hybrid deployments through standardized frameworks for identity federation would also further enhance interoperability for multiple platforms. Inclusion of post-quantum cryptography (PQC) for token signing and mutual TLS would also pre-align the design against post-quantum threats. Large-scale benchmarking investigations and real-world case evaluation are also needed to assess performance and compliance implications for highly regulated industries like finance and healthcare. These extensions would not only improve the resilience of Zero Trust deployments further but also make their use cases among enterprise-scale microservices ecosystems easier.

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