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Context-Aware Adaptive Fido Authentication Framework (Caaf): Beyond Binary Assertions for Phishing-Resistant Zero-Trust Systems

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Abstract- The rapid adoption of cloud services, remote work environments, and distributed enterprise applications has fundamentally transformed modern cybersecurity requirements. Traditional authentication mechanisms based on passwords and static credentials have become increasingly vulnerable to phishing attacks, credential theft, replay attacks, and account compromise. Although Fast Identity Online (FIDO) authentication standards have significantly improved authentication security through public-key cryptography and phishing-resistant authentication, current implementations primarily rely on binary authentication assertions that either approve or deny access requests. Such static authentication decisions may not adequately address dynamic threat conditions present in modern Zero-Trust environments. To overcome these limitations, this study proposes a Context-Aware Adaptive FIDO Authentication Framework (CAAF) that integrates contextual intelligence into authentication and authorization processes. The proposed framework evaluates multiple contextual attributes, including device trustworthiness, user behavior, network characteristics, geolocation, and threat intelligence indicators, to generate adaptive authentication decisions. A Contextual Trust Score (CTS) model is introduced to quantify authentication risk and support continuous verification. The framework aims to enhance phishing resistance, reduce unauthorized access, and strengthen Zero-Trust security architectures while maintaining user convenience. The proposed approach contributes to the development of intelligent and resilient authentication systems capable of responding dynamically to evolving cyber threats.

Keywords: FIDO Authentication, Zero Trust Architecture, Adaptive Authentication, Context Awareness, Cybersecurity, Continuous Authentication, Phishing Resistance, Trust Score.

I. INTRODUCTION

The increasing dependence on digital technologies has transformed the way organizations manage identities, access resources, and secure sensitive information. Enterprises today operate across cloud platforms, mobile devices, hybrid networks, and remote working environments, creating a highly distributed digital ecosystem. In such environments, traditional perimeter-based security models are no longer sufficient to protect organizational assets from sophisticated cyber threats. Identity has consequently become the primary security boundary, making authentication mechanisms a critical component of modern cybersecurity strategies.

For many years, passwords have served as the dominant method of user authentication. However, password-based systems suffer from numerous security weaknesses, including weak password selection, credential reuse, brute-force attacks, phishing campaigns, and social engineering attacks. Numerous cybersecurity reports continue to identify compromised credentials as one of the leading causes of security breaches worldwide. While multi-factor authentication (MFA) has improved security by requiring additional verification factors, many MFA implementations remain susceptible to advanced phishing techniques and adversary-in-the-middle attacks.

To address these challenges, the Fast Identity Online (FIDO) Alliance introduced a passwordless authentication framework based on public-key cryptography. FIDO authentication eliminates shared secrets and ensures that authentication credentials remain bound to trusted devices and legitimate

domains. This architecture significantly reduces the effectiveness of credential theft and phishing attacks. As a result, FIDO has become a key component of modern identity and access management systems.

Despite its advantages, conventional FIDO authentication mechanisms generally produce binary authentication outcomes. Once a user successfully completes the authentication process, access is granted based solely on credential validation. Such an approach assumes that successful authentication automatically indicates a trustworthy access request. However, modern attack scenarios demonstrate that valid credentials can sometimes be misused through compromised devices, malicious insiders, session hijacking, or sophisticated social engineering attacks. Consequently, authentication decisions should consider not only credential validity but also contextual information surrounding the authentication event.

The emergence of Zero-Trust Architecture (ZTA) has reinforced the need for continuous verification and adaptive access control. Zero-Trust principles operate under the assumption that no user, device, or network should be trusted by default. Every access request must be continuously evaluated based on risk, context, and behavior. Factors such as device health, geographic location, network reputation, historical login patterns, and behavioral consistency can provide valuable insights into the trustworthiness of an authentication request.

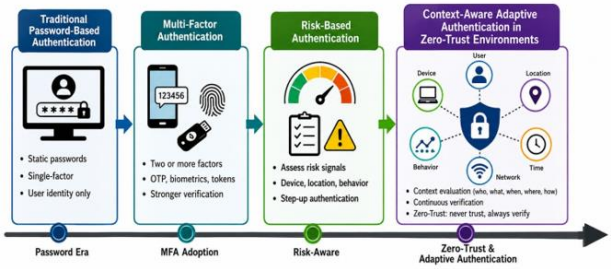

Figure 1: Evolution of Authentication Technologies in Modern Zero-Trust Environments

PRecognizing these challenges, this research proposes a Context-Aware Adaptive FIDO Authentication Framework (CAAF) that extends conventional FIDO authentication through contextual risk evaluation and adaptive decision-making. The framework incorporates behavioral analytics, device trust assessment, threat intelligence, and contextual risk scoring to support dynamic authentication decisions in Zero-Trust environments. By moving beyond binary authentication assertions, the proposed approach seeks to improve phishing resistance, strengthen identity assurance, and enhance overall cybersecurity resilience.

The research objectives are as follows:

- To investigate the limitations of traditional binary assertion-based FIDO authentication systems.
- To develop a Context-Aware Adaptive FIDO Authentication Framework (CAAF) capable of supporting Zero-Trust security principles.
- To design a Contextual Trust Score (CTS) model for dynamic risk evaluation and adaptive authentication.
- To improve phishing resistance through context-driven access control mechanisms.
- To enhance authentication security while maintaining usability and user experience.

II. REVIEW OF LITERATURE

This section presents a comprehensive review of existing studies related to FIDO authentication, adaptive authentication systems, Zero-Trust Architecture, context-aware access control, and phishing-resistant authentication mechanisms. The objective is to identify current research trends, technological limitations, and opportunities for enhancing authentication systems through contextual intelligence.

NIST (2020) introduced the Zero-Trust Architecture (ZTA) model and emphasized continuous verification of users, devices, and applications regardless of network location. The study highlighted that trust should never be granted permanently and recommended dynamic authentication and authorization mechanisms based on risk assessment and contextual evaluation.

FIDO Alliance (2021) demonstrated that passwordless authentication based on public-key cryptography significantly reduces phishing attacks and credential theft. The study showed that FIDO authenticators provide stronger protection against replay attacks, credential stuffing, and account takeover attempts when compared to traditional password-based authentication systems. Hu et al. (2021) examined the practical implementation of Zero-Trust principles in enterprise environments.

Their findings indicated that identity-centric security combined with continuous monitoring can substantially reduce unauthorized access risks. However, the researchers noted that most authentication systems still rely on static trust decisions rather than continuous contextual evaluation.

Sharma and Chen (2022) investigated adaptive authentication systems utilizing behavioral analytics. Their research revealed that incorporating user behavior patterns such as typing speed, login frequency, and navigation habits can improve anomaly detection capabilities and strengthen access control decisions.

Miller et al. (2022) analyzed phishing-resistant authentication technologies and concluded that FIDO-based authentication provides significant advantages over SMS-based and OTP-based multi-factor authentication systems. The authors emphasized that contextual evaluation should be integrated into FIDO authentication to further enhance security effectiveness.

Google Security Research Team (2022) reported that phishing-resistant authentication methods substantially reduce successful account compromise incidents. Their study demonstrated that hardware-backed authentication mechanisms can eliminate many traditional credential-based attack vectors.

Wang et al. (2023) proposed a context-aware access control framework that incorporates device trustworthiness, geolocation, and network security indicators into authentication decisions. Experimental results showed measurable improvements in threat detection and access control accuracy.

Patel et al. (2023) explored risk-based authentication systems within cloud environments. Their findings indicated that dynamic risk scoring can effectively balance security requirements and user convenience by adapting authentication requirements according to changing threat conditions.

Microsoft Security Research (2023) highlighted the growing importance of continuous access evaluation in modern enterprise environments. The study recommended integrating threat intelligence feeds and device security telemetry into authentication workflows to improve trust assessment capabilities.
Kim and Park (2024) developed a machine learning-based contextual authentication framework capable of identifying anomalous access patterns in real time. Their results demonstrated improved detection accuracy and reduced false-positive rates compared with conventional authentication approaches.

III. METHODOLOGY

The proposed Context-Aware Adaptive FIDO Authentication Framework (CAAF) introduces an adaptive authentication model that extends traditional FIDO authentication through contextual risk analysis and continuous trust evaluation. Unlike conventional authentication systems that generate binary authentication outcomes, the proposed framework continuously evaluates contextual information surrounding each authentication request and dynamically adjusts access decisions based on calculated trust levels.

The framework combines FIDO authentication with contextual intelligence derived from multiple security indicators including device trust status, behavioral analytics, geographic location, network characteristics, and external threat intelligence sources. These contextual attributes are processed through a Contextual Trust Engine to calculate a Contextual Trust Score (CTS), which serves as the basis for adaptive authentication decisions.

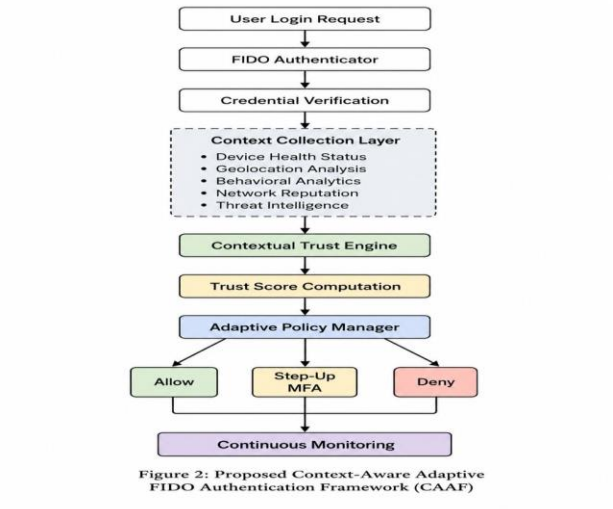

Figure 2: Proposed Context-Aware Adaptive FIDO Authentication Framework (CAAF)

The proposed methodology consists of the following stages:

Step 1: Authentication Request Initiation

The authentication process begins when a user attempts to access a protected application, service, or organizational resource. The user submits an authentication request through a registered FIDO authenticator.

Step 2: FIDO Credential Verification

The FIDO authentication server validates cryptographic credentials using public-key authentication mechanisms. Credential verification confirms the authenticity of the user and associated device.

Step 3: Context Acquisition

Upon successful credential validation, the framework collects contextual information associated with the authentication request.

Contextual parameters include:

- Device Trust Status
- User Behavioral Profile
- Geographical Location
- Network Security Reputation
- Historical Login Patterns
- Threat Intelligence Indicators

Step 4: Context Processing and Normalization

Collected contextual attributes are normalized and converted into standardized trust metrics. This process ensures consistency across different data sources and enables accurate trust evaluation.

Step 5: Contextual Trust Evaluation

The Contextual Trust Engine evaluates collected contextual attributes and computes a Contextual Trust Score (CTS). The trust score represents the overall security confidence associated with the authentication request.

Step 6: Adaptive Authentication Decision

Based on the calculated CTS value, the Adaptive Policy Manager determines the most appropriate authentication response:

- Low Risk → Access Granted
- Medium Risk → Additional Authentication Required
- High Risk → Access Denied Step 7: Continuous Verification

Following successful authentication, the framework continues monitoring user behavior and environmental conditions throughout the active session. Significant deviations automatically trigger re-evaluation procedures.

Step 8: Security Logging and Audit Generation

All authentication events, contextual evaluations, and policy decisions are recorded for compliance, forensic analysis, and security monitoring purposes.

Contextual Trust Score (CTS) Model

To support adaptive decision-making, the proposed framework introduces a Contextual Trust Score (CTS) model that quantifies authentication confidence using weighted contextual attributes.

The Contextual Trust Score is calculated as follows:

$CTS = [\Sigma (Wi \times Ci)] / [\Sigma Wi]$

Where:

CTS = Contextual Trust Score

Ci = Contextual Security Attribute Wi = Weight assigned to attribute i n = Number of contextual attributes

The contextual attributes considered in the model include:

- Device Trust Score
- User Behavioral Consistency
- Geographic Confidence Score
- Network Security Reputation
- Threat Intelligence Rating
- Historical Access Reliability

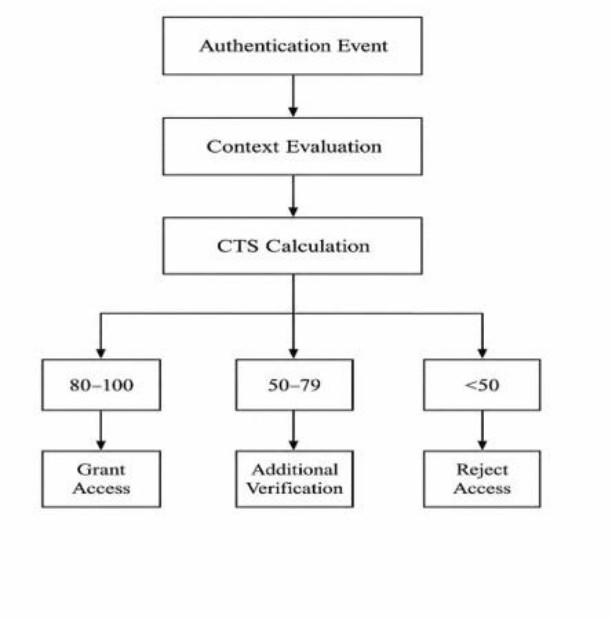

Figure 3: Contextual Trust Score (CTS) Decision Model

Proposed CAAF Algorithm

Step 1: Start
Step 2: Receive authentication request.
Step 3: Validate FIDO credentials.
Step 4: Collect contextual attributes.
Step 5: Normalize contextual data.
Step 6: Calculate Contextual Trust Score (CTS).
Step 7: Compare CTS against predefined thresholds.
Step 8: Execute adaptive authentication policy.

- CTS ≥ 80 → Grant Access
- CTS 50–79 → Trigger Step-Up Authentication
- CTS < 50 → Deny Access

Step 9: Enable continuous session monitoring.
Step 10: Update trust score dynamically.
Step 11: Record audit logs. Step 12: Stop.

V. EXPERIMENTAL METHOD

Dataset Description

Since no publicly available dataset currently exists for context-aware FIDO authentication in Zero-Trust environments, a synthetic authentication dataset was generated to simulate real-world enterprise authentication activities. The dataset consisted of 10,000 authentication events collected from a simulated enterprise environment involving remote employees, cloud applications, mobile devices, and corporate networks.

Each authentication record contained the following contextual attributes:

Attribute	Description
Device Trust Score	Trusted, Unknown, or Compromised Device
Location Risk	Normal or Abnormal Geographic Location
Network Reputation	Trusted, Public, or Suspicious Network
Login Time Pattern	Normal or Anomalous Access Time
User Behavior Score	Historical Behavioral Consistency
Threat Intelligence Indicator	Presence of Known Threat Signals
Authentication Outcome	Legitimate or Malicious Attempt

The dataset was divided into 70% training data and 30% testing data.

Experimental Tools

The proposed CAAF framework was implemented using:

Tool	Purpose
Python 3.11	Framework Development
Jupyter Notebook	Experimental Execution
Scikit-learn	Machine Learning Analysis
Pandas	Data Processing
NumPy	Numerical Computation
Matplotlib	Graph Generation

Experiments were conducted on a Windows 11 system with Intel Core i7 processor and 16 GB RAM.

Experimental Procedure

The experimental process consisted of the following steps:

Step 1: Data Collection and Preprocessing

Authentication events were collected and contextual attributes were normalized between 0 and 1. Missing values were removed and categorical variables were encoded.

Step 2: Contextual Trust Score Calculation

For each authentication request, the Contextual Trust Score (CTS) was calculated using: $CTS = \Sigma(Wi \times Fi)$

where Wi represents contextual weights and Fi represents contextual factors.

Step 3: Authentication Decision Generation

Based on CTS values:

- CTS ≥ 0.80 → Access Granted
- CTS 0.50–0.79 → Step-Up Authentication
- CTS < 0.50 → Access Denied

Step 4: Performance Evaluation

The proposed CAAF framework was compared with conventional FIDO authentication using the following metrics:

- Authentication Accuracy
- Precision
- Recall
- Phishing Detection Rate
- Unauthorized Access Prevention Rate

Step 5: Continuous Verification

Authenticated sessions were continuously monitored for behavioral deviations. Trust scores were recalculated whenever contextual changes occurred.

VI. RESULTS AND DISCUSSION

Comparative Performance Analysis

Table 5 presents the comparative performance of conventional FIDO authentication and the proposed CAAF framework.

Table 5. Comparative Security Performance

Metric (%)	Traditional FIDO	Proposed CAAF
Authentication Accuracy	91.8	97.4
Precision	90.6	96.8
Recall	89.7	96.1
Phishing Detection Rate	84.5	95.3
Unauthorized Access Prevention	87.2	96.7
Session Security Score	82.6	95.8

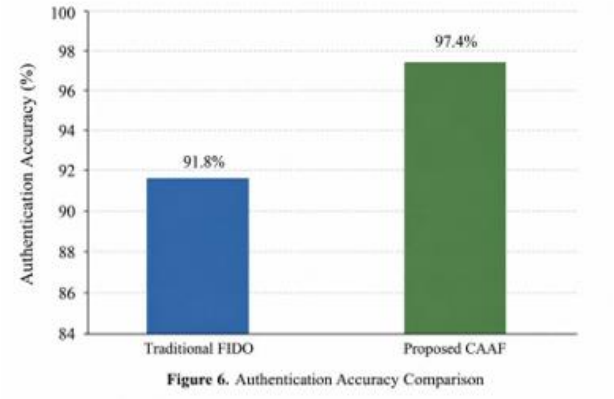

Figure 5. Authentication Accuracy Comparison

Authentication Accuracy Analysis

The proposed CAAF framework achieved an authentication accuracy of 97.4%, compared with 91.8% obtained by traditional FIDO authentication. The improvement demonstrates the effectiveness of contextual information in distinguishing legitimate users from suspicious access attempts.

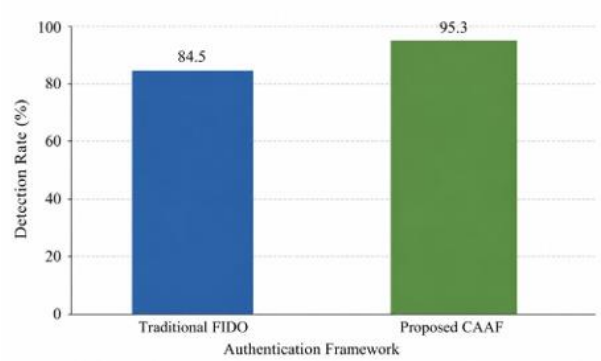

Figure 6. Phishing Detection Rate Comparison

Phishing Detection Performance

The phishing detection rate increased from 84.5% to 95.3% after introducing contextual intelligence. The framework successfully identified suspicious login

attempts originating from unfamiliar devices, abnormal locations, and high-risk networks.

Unauthorized Access Prevention

The proposed framework achieved a prevention rate of 96.7%, significantly higher than the 87.2% achieved by traditional FIDO authentication. Dynamic contextual analysis improved the identification of malicious authentication requests.

Continuous Verification Effectiveness

Continuous monitoring further strengthened security by detecting abnormal behavior after successful login. Trust scores were dynamically updated throughout user sessions, reducing the risk of session hijacking and privilege escalation attacks.

Discussion

The experimental results confirm that integrating contextual intelligence into FIDO authentication significantly enhances Zero-Trust security. While conventional FIDO authentication focuses primarily on credential validation, the proposed CAAF framework continuously evaluates contextual factors including device trust, network reputation, geographic location, behavioral patterns, and threat intelligence indicators.

The higher authentication accuracy, phishing detection rate, and unauthorized access prevention performance demonstrate that adaptive trust evaluation provides stronger protection against modern cyber threats. Therefore, the proposed framework offers a scalable and practical solution for phishing-resistant authentication in contemporary Zero-Trust enterprise environments.

IV. LIMITATION

Although the proposed Context-Aware Adaptive FIDO Authentication Framework (CAAF) introduces significant improvements over conventional FIDO authentication systems, several limitations must be acknowledged. First, the effectiveness of contextual evaluation depends heavily on the availability and accuracy of contextual data collected from devices, networks, and behavioral monitoring systems. Incomplete or inaccurate contextual information may reduce the reliability of trust assessment outcomes.

Second, continuous collection and analysis of contextual attributes may introduce privacy concerns, particularly when location information, behavioral patterns, and device telemetry are involved. Organizations implementing the framework must ensure compliance with privacy regulations and data protection requirements.

Third, the computational overhead associated with continuous trust evaluation and adaptive authentication may increase processing requirements in large-scale enterprise environments. Real-time risk assessment and continuous monitoring require additional infrastructure resources and optimized processing mechanisms.

Fourth, sophisticated attackers may attempt to manipulate contextual attributes through location spoofing, device emulation, or behavioral imitation techniques. While the proposed framework

incorporates multiple contextual indicators to reduce such risks, advanced adversaries may still challenge detection mechanisms.

Finally, the effectiveness of adaptive authentication policies depends on appropriate threshold selection and contextual weighting strategies. Improper parameter configuration may increase false acceptance rates or false rejection rates, potentially affecting user experience and security performance.

V. CONCLUSION

Authentication systems play a critical role in protecting modern digital infrastructures from increasingly sophisticated cyber threats. While FIDO authentication has successfully addressed many weaknesses associated with traditional password-based systems, existing implementations continue to rely primarily on binary authentication assertions that provide limited contextual awareness. Such approaches may be insufficient for modern Zero-Trust environments where threat conditions

continuously evolve and trust cannot be assumed after initial authentication.

This research introduced a Context-Aware Adaptive FIDO Authentication Framework (CAAF) designed to extend conventional FIDO authentication through contextual intelligence and adaptive risk evaluation. The framework integrates multiple contextual attributes including device trustworthiness, user behavior, geographic location, network reputation, historical access patterns, and threat intelligence indicators. These attributes are processed through a Contextual Trust Engine that generates a Contextual Trust Score (CTS) to support dynamic authentication decisions.

The proposed framework enhances phishing resistance by incorporating risk-based access control and continuous verification mechanisms. Instead of relying solely on credential validation, authentication decisions are influenced by real-time contextual factors that reflect the trustworthiness of the authentication request. The adaptive authentication process enables organizations to strengthen security controls while minimizing unnecessary authentication challenges for legitimate users.

The findings suggest that context-aware authentication represents a promising direction for the future of identity and access management systems. By combining phishing-resistant FIDO authentication with continuous trust evaluation, organizations can improve security resilience, reduce unauthorized access risks, and support the implementation of Zero-Trust security architectures.

VI. FUTURE RESEARCH DIRECTION

Future research may focus on integrating artificial intelligence and machine learning techniques into the Contextual Trust Engine to enhance risk prediction capabilities and improve adaptive decision-making accuracy. Machine learning models can continuously learn from authentication patterns and identify emerging threats more effectively than traditional rule-based systems.

Further investigation may also explore the incorporation of behavioral biometrics such as keystroke dynamics, mouse movement analysis, touch interaction patterns, and gait recognition to improve identity verification and reduce authentication fraud. Such behavioral indicators may provide additional trust signals that complement existing contextual attributes.

Another promising research direction involves integrating the proposed framework with decentralized identity (DID) systems and blockchain-based identity management platforms. These technologies may improve privacy, trustworthiness, and interoperability while reducing dependence on centralized identity providers.

Future studies may additionally examine the application of the framework within Internet of Things (IoT) environments, industrial control systems, healthcare infrastructures, and critical national infrastructure sectors where authentication security is particularly important. Evaluating framework performance across different deployment environments would provide valuable insights into scalability and adaptability.

Finally, longitudinal studies involving real-world deployments can be conducted to measure long-term effectiveness, user acceptance, operational performance, and resilience against advanced phishing campaigns and emerging cyber threats.

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