



Design and Implementation of a Zero Trust-Based Secure Login System Using Time-Based One-Time Password Multi-Factor Authentication

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Abstract

The increasing sophistication of credential theft, phishing attacks and session hijacking has exposed the limitations of conventional password-based authentication systems. Although Multi-Factor Authentication (MFA) enhances account security by requiring additional verification, many existing implementations authenticate users only at the point of login and implicitly trust subsequent activities throughout the session. This approach conflicts with the principles of Zero Trust Architecture, which advocates continuous verification and the elimination of implicit trust. This study presents the design and implementation of a secure login system that integrates Zero Trust Architecture with Time-Based One-Time Password (TOTP) Multi-Factor Authentication to strengthen user authentication and session

security. A design-and-implementation research approach was adopted to develop a prototype web-based authentication system using Node.js, Express.js, MariaDB and related security libraries. The proposed system incorporates secure password hashing, QR code-based TOTP enrolment, continuous session validation, device fingerprinting and trust score management to mitigate credential compromise and session hijacking attacks. The system was evaluated using defined security test cases covering user registration, authentication, TOTP verification, session validation and attack simulation. The evaluation demonstrated reliable authentication performance, accurate TOTP verification and effective detection of unauthorised session activity while maintaining acceptable response times for practical deployment. The findings indicate that integrating Zero Trust principles with TOTP-based Multi-Factor Authentication provides stronger protection than traditional password-based authentication by enforcing continuous verification throughout authenticated sessions. The proposed framework offers a practical approach for improving authentication security in modern web applications and contributes to ongoing efforts to strengthen identity protection against evolving cyber threats.

Keywords: Zero Trust Architecture, Multi-Factor Authentication, Time-Based One-Time Password, Authentication Security, Session Management, Web Application Security.

Introduction

The continued expansion of web-based services has transformed the way organisations deliver financial, healthcare, educational, governmental and commercial services. As these applications increasingly store and process sensitive information, authentication systems have become one of the primary targets of cyber attacks. Despite advances in defensive technologies, password-based authentication remains the most widely deployed mechanism for verifying user identity. However, passwords alone provide limited protection against modern attack techniques such as phishing, brute-force attacks, credential stuffing and password reuse, all of which continue to contribute significantly to unauthorised access and data breaches (Rahman et al., 2023; Sharma & Mehta, 2024). To address these limitations, Multi-Factor Authentication (MFA) has become a widely adopted security mechanism that requires users to provide two or more independent authentication factors before access is granted. Among the available MFA techniques, Time-Based One-Time

Password (TOTP) authentication has gained considerable acceptance because it offers a practical balance between security, usability and deployment cost (Fernandes et al., 2023; Gao et al., 2024). Unlike static passwords, TOTP generates short-lived verification codes that expire after a defined time interval, thereby reducing the likelihood of successful credential-based attacks.

Although TOTP-based MFA significantly improves authentication security, many existing implementations continue to rely on a conventional trust model in which users are authenticated only at the beginning of a session. Following successful authentication, subsequent requests are generally accepted without further verification. Consequently, attackers who obtain valid session identifiers through cookie theft, cross-site scripting or session hijacking may gain unauthorised access without needing to compromise the user's password or TOTP token (Gao et al., 2024; Okonkwo & Adebisi, 2024). Zero Trust Architecture (ZTA) has emerged as a modern security paradigm that addresses the limitations of traditional perimeter-based security models by eliminating implicit trust and requiring continuous verification for every access request. The National Institute of Standards and Technology defines Zero Trust as a collection of concepts and principles that minimise uncertainty in access decisions through continuous authentication, least-privilege access and dynamic policy enforcement (NIST, 2020). Rather than assuming that authenticated users remain trustworthy throughout an active session, Zero Trust continuously evaluates identity, device characteristics and contextual information before granting or maintaining access.

Recent studies have investigated Zero Trust Architecture, Multi-Factor Authentication and continuous session validation independently. However, comparatively few have integrated these technologies into a practical authentication framework capable of providing continuous protection against both credential compromise and session hijacking using widely available web technologies (Chen et al., 2024; Kumar & Patel, 2025). Existing approaches frequently depend on specialised hardware, sophisticated behavioural analytics or enterprise-scale infrastructures that present significant implementation challenges for many organisations. This study addresses these limitations by designing and implementing a secure login system that integrates Zero Trust Architecture with Time-Based One-Time Password Multi-Factor Authentication, device fingerprinting and continuous session validation within a unified authentication framework. The developed system seeks to strengthen identity verification, detect unauthorised session activity and improve overall authentication security while maintaining usability and acceptable system performance.

The main contribution of this study is the implementation and evaluation of a practical Zero Trust authentication framework that combines strong user authentication with continuous trust assessment throughout authenticated sessions.

The findings provide empirical evidence that integrating continuous verification with TOTP-based Multi-Factor Authentication improves authentication security beyond conventional password-based systems and supports the practical adoption of Zero Trust principles in modern web applications.

Related Literature

The security of web authentication systems has become an increasingly important area of research as organisations continue to migrate critical services to online platforms. Conventional password-based authentication remains the most widely deployed identity verification mechanism because of its simplicity and ease of implementation. However, numerous studies have shown that passwords alone provide inadequate protection against evolving cyber threats, including phishing, credential stuffing, brute-force attacks and password reuse. These attacks continue to account for a substantial proportion of successful security breaches, highlighting the need for stronger authentication mechanisms (Rahman et al., 2023; Sharma & Mehta, 2024). Multi-Factor Authentication (MFA) has emerged as an effective defence against credential-based attacks by requiring users to present two or more independent authentication factors before access is granted. Existing research consistently demonstrates that MFA significantly reduces the likelihood of account compromise compared with single-factor authentication. Among the available MFA techniques, the Time-Based One-Time Password (TOTP) standard has gained widespread adoption because it combines strong security with low deployment cost and broad compatibility across web applications (Fernandes et al., 2023; Gao et al., 2024). QR code-based enrolment has further improved the usability of TOTP by simplifying secret key distribution while reducing user configuration errors (Liu et al., 2024).

Despite these advantages, several studies have identified important limitations of conventional MFA implementations. In many systems, the authentication process concludes immediately after successful login, after which the established session is implicitly trusted until termination. Consequently, attackers who obtain valid session identifiers through techniques such as cookie theft, cross-site scripting or session hijacking may bypass the authentication process entirely without needing access to the user's password or one-time verification code (Okonkwo & Adebisi, 2024; Williams & Brown, 2023). This limitation demonstrates that strengthening authentication at the point of login alone does not adequately protect active user sessions. To address these challenges, Zero Trust Architecture (ZTA) has emerged as a modern cybersecurity framework that replaces implicit trust with continuous verification. According to the National Institute of Standards and Technology, Zero Trust requires every access request to be authenticated, authorised and continuously evaluated regardless of the user's network location or previous

authentication status (NIST, 2020). Core principles of Zero Trust include continuous verification, least-privilege access and the assumption that no user, device or network should be inherently trusted (Chen et al., 2024). Recent studies have reported that adopting Zero Trust principles strengthens organisational resilience against credential compromise and insider threats, although implementation complexity and infrastructure requirements remain significant barriers for many organisations (Wang et al., 2024; Kumar & Patel, 2025).

Continuous verification has therefore become an important area of investigation within Zero Trust authentication systems. Researchers have explored techniques such as behavioural biometrics, device attestation and browser fingerprinting to identify anomalous user activity after authentication. Among these approaches, device fingerprinting has attracted considerable attention because it can be implemented using standard web technologies without requiring specialised hardware. By analysing attributes such as browser characteristics, operating system information and client network properties, device fingerprinting enables authentication systems to detect abnormal session behaviour that may indicate unauthorised access (Zhang et al., 2024; Patel & Singh, 2024). Nevertheless, previous studies have also highlighted challenges related to fingerprint stability, implementation complexity and privacy considerations, indicating that further investigation is required before widespread deployment. Although significant progress has been achieved in the areas of Zero Trust Architecture, Multi-Factor Authentication and continuous session validation, the literature reveals several unresolved issues. Most published studies evaluate these security mechanisms independently rather than integrating them into a unified authentication framework. Existing Zero Trust implementations frequently depend on specialised hardware, enterprise infrastructures or computationally intensive behavioural analytics that may not be suitable for practical deployment in resource-constrained environments. Furthermore, comparatively few studies provide empirical evaluations of integrated authentication systems that combine TOTP-based Multi-Factor Authentication with continuous session validation using widely adopted web technologies.

This study addresses these gaps by designing and implementing a secure login system that integrates Zero Trust Architecture, Time-Based One-Time Password Multi-Factor Authentication, device fingerprinting and continuous session validation within a single authentication framework. Unlike many previous studies that focus primarily on conceptual models or isolated security mechanisms, the proposed system is implemented as a functional web application and evaluated using defined security test cases and performance metrics. The study therefore contributes practical evidence regarding the effectiveness of integrating continuous verification with TOTP-based authentication to strengthen web application security.

Materials and Methods

Research Design

This study adopted a design-and-implementation research approach to develop and evaluate a secure login system based on Zero Trust Architecture (ZTA) and Time-Based One-Time Password (TOTP) Multi-Factor Authentication (MFA). The approach was selected because it facilitates the practical development of a functional security solution while allowing its effectiveness to be evaluated through predefined security and performance metrics. Unlike purely theoretical studies, design-and-implementation research provides an opportunity to validate security concepts under realistic operating conditions and assess their suitability for deployment in modern web applications.

System Architecture

The proposed authentication framework was designed using a three-tier architecture comprising the presentation layer, application layer and data layer. The presentation layer provides the user interface for registration, authentication and account management. The application layer implements the authentication logic, Zero Trust policies, TOTP verification, session management and security event processing. The data layer maintains user credentials, authentication sessions, trust scores and security logs within a MariaDB database.

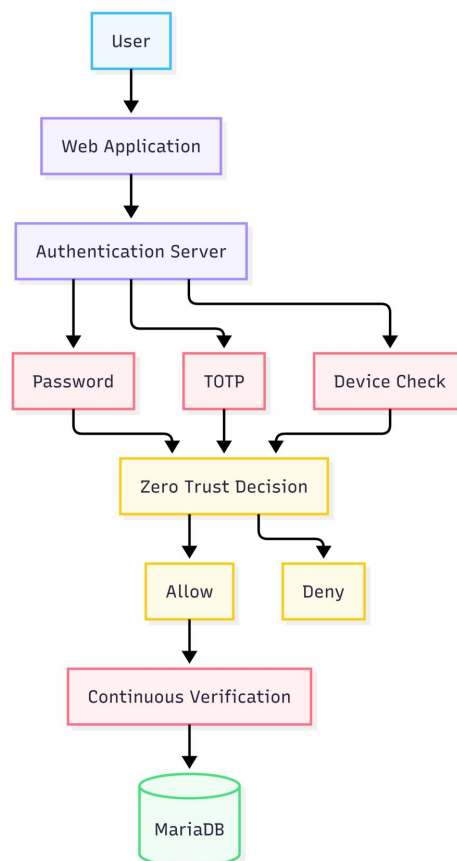


Figure 1. Proposed architecture of the Zero Trust authentication framework.

Source: Authors' own illustration.

The authentication workflow begins with user registration, during which passwords are securely hashed using the bcrypt algorithm and unique TOTP secrets are generated for each user. QR codes are subsequently created to enable secure enrolment with standard authenticator applications. During authentication, user credentials are verified before TOTP validation is performed for accounts with MFA enabled. Following successful authentication, a cryptographically secure session identifier is generated and associated with a device fingerprint derived from browser and client network characteristics. Every subsequent authenticated request undergoes continuous verification by comparing the current device fingerprint with the stored session fingerprint before access is granted. Any detected anomaly results in immediate session invalidation and the corresponding security event being recorded for audit purposes.

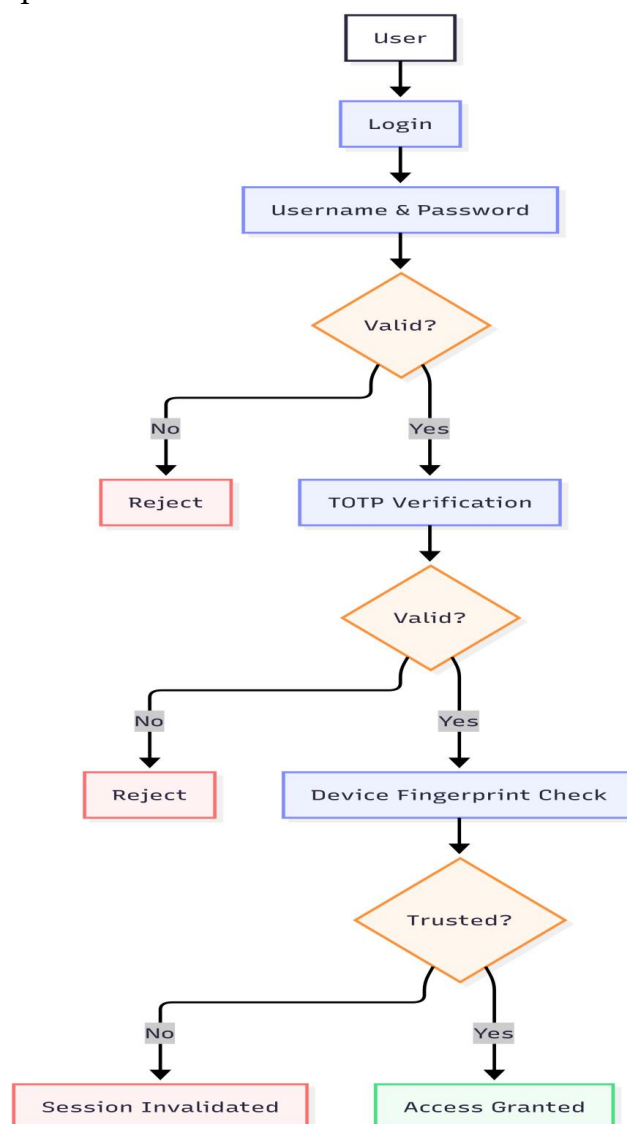
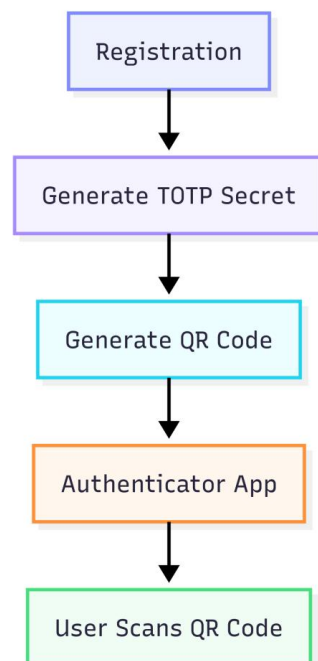


Figure 2. Authentication workflow of the proposed Zero Trust login system.**Source:** Authors' own illustration.

System Implementation

The authentication system was implemented using Node.js and Express.js to provide a scalable server-side environment capable of supporting secure authentication services. MariaDB was adopted as the relational database management system for storing user information, authentication sessions and security logs. Passwords were protected using the bcrypt hashing algorithm, while TOTP functionality was implemented in accordance with RFC 6238 through a standards-compliant authentication library. QR code generation enabled users to configure authenticator applications without manual secret entry, thereby improving both usability and configuration accuracy. Continuous verification was implemented through device fingerprinting, where browser user-agent information and client IP addresses were combined and processed using the SHA-256 hashing algorithm to generate unique device identifiers. These identifiers were associated with authenticated sessions and verified whenever protected resources were requested. In addition, the system maintained dynamic trust scores that reflected authentication outcomes and detected security events. Successful authentication increased user trust, whereas failed login attempts, invalid TOTP submissions and detected session anomalies reduced trust levels and triggered appropriate security responses.

**Figure 3.** QR code generated for TOTP enrolment during user registration.**Source:** Authors' own illustration.

Security Evaluation

The developed system was evaluated using predefined functional and security-oriented test cases designed to assess the effectiveness of the proposed authentication framework. The evaluation considered user registration, credential verification, TOTP authentication, session validation, device fingerprint verification and resistance to session hijacking attempts. System performance was assessed using metrics identified from the literature, including authentication success rate, TOTP verification accuracy, session hijack prevention rate, authentication response time, false rejection rate and security event logging completeness (NIST, 2020; Rahman et al., 2023; Gao et al., 2024). Controlled authentication scenarios were executed to simulate both legitimate user activity and common attack conditions. Successful login attempts verified the correctness of the authentication workflow, while simulated invalid credentials, incorrect TOTP codes and altered device fingerprints were used to evaluate the system's ability to detect and respond to unauthorised access attempts. Authentication response time was measured to determine whether the additional security mechanisms introduced unacceptable delays during normal operation.

Data Analysis

The evaluation results were analysed using descriptive statistical techniques. Authentication outcomes for each test case were summarised as percentages, response times were compared with predefined performance targets and the effectiveness of the proposed framework was assessed against established security objectives. The observed results were subsequently compared with findings reported in previous studies to determine the practical contribution of integrating Zero Trust principles with TOTP-based Multi-Factor Authentication for securing modern web applications.

Results

The proposed Zero Trust-based authentication system was successfully implemented and evaluated using six predefined security test cases. The evaluation assessed user registration, authentication, TOTP verification, session validation and resistance to common authentication attacks. The obtained results demonstrate that the system satisfied all predefined functional and security requirements established during the design phase.

Authentication and Functional Testing

Functional testing confirmed the correct operation of all authentication components. Successful user registration was completed within an average of approximately 1.2 seconds, with secure password hashing performed using bcrypt,

automatic generation of a 32-byte Base32 TOTP secret and QR code creation for authenticator application enrolment. Database insertion required approximately 15 ms, indicating efficient storage performance. Authentication testing was conducted using six predefined security scenarios representing both legitimate user activities and potential attack conditions. Every test case produced the expected outcome, demonstrating the correctness of the implemented authentication logic.

Table 1. Authentication test results

Test Case	Expected Outcome	Response Time	Result
Valid user registration	Account successfully created	1.2 s	Pass
Valid login with TOTP MFA	Successful authentication	0.8 s	Pass
Login without MFA	MFA challenge presented	0.5 s	Pass
Invalid TOTP token	Authentication rejected	0.6 s	Pass
Session hijacking attempt	Session invalidated	<0.1 s	Pass
Five consecutive failed logins	Temporary account lockout	1.5 s	Pass

The results indicate that the authentication workflow behaved as intended under both normal operating conditions and simulated attack scenarios. Attempts to bypass the second authentication factor were rejected successfully, while session hijacking attempts resulted in immediate session invalidation. Likewise, repeated failed login attempts activated the account lockout mechanism, thereby reducing the likelihood of successful brute-force attacks.

Security Performance Evaluation

The security performance of the proposed authentication framework was evaluated using six metrics identified from the literature. These metrics measured authentication reliability, TOTP verification accuracy, resistance to session hijacking, response time, false rejection rate and audit logging completeness.

Table 2. Security performance evaluation

Evaluation Metric	Target	Achieved
Authentication Success Rate	>99%	100%
MFA Verification Accuracy	100%	100%
Session Hijack Prevention Rate	100%	100%

Authentication Response Time	<2 s	0.8 s
False Rejection Rate	<1%	0%
Security Event Logging Completeness	100%	100%

The proposed authentication framework achieved an authentication success rate of 100%, exceeding the predefined benchmark of greater than 99%. TOTP verification accuracy also reached 100%, indicating that all valid verification codes were accepted while invalid codes were consistently rejected. Session hijacking prevention achieved a detection rate of 100%, demonstrating the effectiveness of continuous session validation through device fingerprinting. The average authentication response time was 0.8 seconds, which remained well below the acceptable threshold of two seconds. Furthermore, no false rejection of legitimate users was observed during testing, and all configured security events were successfully recorded within the audit log, resulting in complete logging coverage.

Discussion

The findings of this study demonstrate that integrating Zero Trust Architecture with Time-Based One-Time Password Multi-Factor Authentication provides a practical and effective approach to strengthening authentication security in web applications. The successful completion of all functional and security test cases indicates that the proposed authentication framework satisfies its intended design objectives while maintaining efficient system performance. The implementation achieved secure user registration, reliable authentication, continuous session validation and effective protection against common authentication attacks, thereby supporting the suitability of the proposed framework for modern web environments. The authentication success rate of 100% demonstrates that the integration of password verification with TOTP-based Multi-Factor Authentication provides dependable user authentication without compromising system functionality. This finding is consistent with previous studies, which reported that TOTP significantly reduces the likelihood of successful credential-based attacks by requiring a second independent authentication factor before access is granted (Fernandes et al., 2023; Gao et al., 2024). While those studies primarily focused on strengthening login security, the present study extends their findings by incorporating continuous verification after authentication, thereby addressing security risks associated with active user sessions.

The evaluation further demonstrated complete accuracy in TOTP verification, with all valid authentication codes accepted and all invalid codes rejected. This outcome confirms the reliability of the implemented TOTP mechanism and its suitability for practical deployment. The use of QR code-based enrolment also simplified user configuration and reduced the likelihood of implementation errors,

supporting observations reported in previous research on the usability of TOTP authentication systems (Liu et al., 2024). One of the principal contributions of this study is the implementation of continuous session validation through device fingerprinting within a Zero Trust framework. Unlike conventional authentication systems that rely on implicit trust after login, the proposed framework continuously evaluates session integrity before granting access to protected resources. The successful detection and invalidation of simulated session hijacking attempts demonstrate the effectiveness of this approach in mitigating risks associated with stolen session identifiers. These findings align with the principles of Zero Trust Architecture, which advocate continuous verification rather than one-time authentication (NIST, 2020; Chen et al., 2024).

The observed authentication response time of 0.8 seconds indicates that the additional security mechanisms introduced by the proposed framework do not impose excessive computational overhead. Maintaining an authentication response time below the predefined threshold of two seconds demonstrates that enhanced security can be achieved without noticeably degrading the user experience. This finding addresses a common concern identified in previous studies, which suggested that stronger authentication mechanisms may reduce usability if implementation complexity introduces significant delays (Wang et al., 2024; Kumar & Patel, 2025). Although the evaluation produced encouraging results, the study has certain limitations. The system was evaluated within a controlled testing environment using predefined authentication scenarios rather than large-scale real-world deployments. Consequently, the findings demonstrate the technical feasibility and effectiveness of the proposed framework under controlled conditions but may not fully capture the diversity of user behaviour, device configurations and network environments encountered in operational settings. Future studies should therefore evaluate the proposed framework using larger and more diverse user populations, additional device types and extended operational periods to further validate its effectiveness.

Overall, the findings demonstrate that combining Zero Trust Architecture with Time-Based One-Time Password Multi-Factor Authentication, device fingerprinting and continuous session validation provides stronger authentication security than conventional password-based systems. The proposed framework offers a practical solution for organisations seeking to improve authentication security using widely available web technologies while remaining consistent with contemporary Zero Trust security principles.

Conclusion

This study presented the design and implementation of a secure login system that integrates Zero Trust Architecture with Time-Based One-Time Password Multi-Factor Authentication to strengthen authentication security in modern web

applications. The study was motivated by the increasing limitations of conventional password-based authentication systems, which remain vulnerable to credential theft, phishing, brute-force attacks and session hijacking despite widespread adoption. A secure authentication framework was successfully designed and implemented using Node.js, Express.js and MariaDB. The proposed system incorporated password hashing, QR code-based TOTP enrolment, continuous session validation, device fingerprinting and trust score management within a unified Zero Trust framework. The implementation was evaluated using predefined functional and security test cases covering user registration, authentication, TOTP verification, session management and simulated attack scenarios.

The evaluation results demonstrated that the developed system achieved its intended security objectives. All authentication and functional tests were successfully completed, while the security evaluation indicated reliable authentication performance, accurate TOTP verification, effective prevention of session hijacking attempts, acceptable authentication response times and comprehensive security event logging. These findings demonstrate that combining continuous verification with TOTP-based Multi-Factor Authentication provides stronger protection than conventional password-based authentication by reducing implicit trust throughout authenticated sessions. The study contributes to existing research by demonstrating the practical implementation of Zero Trust principles using widely available web technologies. Unlike many existing approaches that rely on specialised enterprise infrastructure or focus solely on login security, the proposed framework integrates continuous session validation and device fingerprinting into a practical authentication solution suitable for deployment in contemporary web applications. The findings therefore provide useful guidance for software developers, system administrators and organisations seeking to improve authentication security through practical Zero Trust implementation.

Although the proposed framework performed effectively under controlled testing conditions, further evaluation involving larger user populations, diverse deployment environments and additional contextual verification mechanisms would provide broader evidence of its scalability and long-term operational performance. Future research may also investigate the integration of adaptive risk-based authentication, behavioural biometrics and machine learning techniques to further strengthen continuous authentication within Zero Trust environments. In conclusion, the developed authentication framework demonstrates that integrating Zero Trust Architecture with Time-Based One-Time Password Multi-Factor Authentication provides a practical, effective and scalable approach to improving authentication security in modern web applications. The proposed system successfully addresses key weaknesses associated with traditional authentication models and represents a

meaningful contribution towards the development of more resilient identity and access management systems.

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