A Secure and Adaptive Two-Factor Authentication System: Design, Implementation, and Evaluation for Enhanced Security and Usability

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**Abstract.** Two-factor authentication (2FA) has become essential for protecting user accounts from unauthorized access. However, despite its security benefits, many users hesitate to adopt 2FA due to usability challenges and vulnerabilities such as phishing attacks and SIM swapping. This work aims to design and evaluate a secure, efficient, and user-friendly 2FA system that enhances security while minimizing authentication friction. The proposed system integrates multiple authentication methods, including time-based one-time passwords (TOTP), email verification, and SMS-based OTPs, allowing flexibility in user authentication. To address common security concerns, the system employs strong encryption mechanisms, secure authentication protocols, and an intuitive user interface to balance security with usability. A comprehensive evaluation was conducted, including security testing, usability analysis, and performance benchmarking. Test results indicate that the proposed system successfully mitigates phishing attacks by 95% and reduces authentication time by 30% compared to traditional SMS-based OTP systems. Additionally, user acceptance tests revealed a 40% increase in user satisfaction due to the availability of multiple authentication methods and a simplified login process. By enhancing both security and user experience, this system supports ongoing cybersecurity efforts and provides a scalable, efficient, and user-friendly solution for secure authentication in various online applications.

# Introduction

## The Importance of Strong Authentication

In today's digital landscape, Identity and Access Management (IAM) has become a critical focus for enterprises seeking to manage user identities and control access to sensitive resources. Within this framework, strong authentication plays a central role, providing the necessary foundation for secure access. Unlike traditional password-based authentication, which suffers from well-known shortcomings, strong authentication enables organizations to verify user identities with a high degree of certainty, thereby enhancing online trust. As the reliance on online services grows, so does the need for robust authentication methods. Industry predictions indicate that strong authentication will play an increasingly important role in both enterprise and consumer environments, underscoring the urgency and relevance of developing more effective solutions.

## Limitations of Traditional Authentication and the Rise of 2FA

Traditional password-based authentication has notable limitations, making it vulnerable to phishing and pharming attacks. Phishing deceives users into revealing credentials via fake emails and sites [1], while pharming manipulates DNS to redirect users to fraudulent pages [2]. In June 2021 alone, 222,127 unique phishing attacks were reported, highlighting the scale of the threat. These vulnerabilities stress the need for stronger mechanisms. Multi-factor authentication (2FA) enhances security by combining something you know (password) with something you have (device) or are (biometric). Technologies like Google 2-Step and FIDO U2F demonstrate the shift to more robust, layered authentication methods.

# RELATED WORKS

## An Efficient Stacked-LSTM Based User Clustering for 5G NOMA Systems

Non-orthogonal multiple access (NOMA) has emerged as a promising technology to meet the increasing demands of 5G and future wireless communication systems. NOMA allows multiple users to share the same time-frequency resources, thereby increasing spectral efficiency compared to traditional orthogonal multiple access (OMA) schemes. As explained in [3], NOMA was initially considered for 5G New Radio (NR) by 3GPP. However, while extensively studied, it was ultimately decided not to include NOMA in the first phase of 5G NR, with the possibility of its adoption in later releases or beyond 5G systems.

The core idea of NOMA lies in multiplexing users in either the power domain or the code domain. In power-domain NOMA, users are allocated different power levels based on their channel conditions, while in code-domain NOMA, users are separated by distinct codes. This approach enables NOMA to achieve significant benefits, including enhanced spectral efficiency, improved user fairness, and massive connectivity, which are crucial for supporting the diverse requirements of 5G and beyond.

Despite its advantages, NOMA also presents several challenges. These include increased receiver complexity due to the need for successive interference cancellation (SIC), as well as challenges related to power allocation, user pairing, and interference management. Consequently, research is ongoing in various areas to address these challenges and further improve the performance of NOMA systems.

Looking beyond 5G, NOMA is expected to play an even more critical role in enabling new applications and services, such as enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC). The ability of NOMA to support a massive number of connected devices and provide high data rates makes it a key candidate for future wireless generations. This literature review will delve further into the status, challenges, and future directions of NOMA research, providing a comprehensive overview of its potential to revolutionize wireless communication.

## Strong Authentication: An Essential Component of Identity and Access Management

Identity and Access Management (I&AM) has become a critical focus for leading enterprises across industries, driving a need to re-evaluate traditional approaches to user authentication. I&AM strategies aim to provide more secure, efficient, and flexible ways to manage user identities and access privileges. Within this framework, strong authentication plays a vital role, providing a higher level of certainty in verifying user identities compared to traditional password protection, thereby enhancing online trust.

Traditional password authentication, while widely used, suffers from several weaknesses. In many organizations, the proliferation of applications has led to distributed, decentralized infrastructures for identity management, which are costly to manage and maintain. Furthermore, users often struggle with password fatigue, which leads to poor password choices and security practices. Most significantly, passwords are vulnerable to various attacks, including cracking tools and phishing, making them an inadequate security measure for high-value applications and data.

Strong authentication offers a more robust alternative. It often involves the use of multi-factor authentication, which combines two or three different authentication factors: something the user knows (e.g., password, PIN), something the user has (e.g., token, smart card), and something the user is (e.g., biometric characteristic). This multi-layered approach significantly enhances security by making it much harder for an attacker to compromise a user's identity.

In the context of emerging technologies like IoT and cloud computing, strong authentication is particularly crucial. IoT devices and cloud services introduce new challenges due to their distributed nature and the need for remote access. To address these challenges, techniques such as digital certificates and local certification authorities are being employed to provide strong user authentication in these environments.

The adoption of strong authentication provides numerous benefits. It enhances security, reduces the risk of online crime, and enables organizations to verify user identities with a high degree of certainty. Strong authentication also improves user experience by reducing password fatigue and increasing trust in online services. Ultimately, strong authentication is an essential component of I&AM, providing the foundation for secure and reliable access to digital resources in today's interconnected world.

# Research Methodology

This research employs a mixed-methods approach to design and evaluates a novel two-factor authentication (2FA) system. A mixed-methods approach is appropriate as it allows for a comprehensive assessment of both the system's technical performance (security, efficiency) and its user experience (usability, user satisfaction). This reflects the increasing recognition of the importance of integrating quantitative and qualitative approaches in security research to achieve a comprehensive understanding [4].

## System Design

The first phase of the research involved the design of the 2FA system. The system was designed to integrate multiple authentication methods, providing users with flexibility and choice. The specific methods included:

* Time-based One-Time Passwords (TOTP): TOTP was implemented based on the standard algorithm specified in RFC 6238. This involves the use of a shared secret key between the server and the user's authentication device, which is used to generate time-sensitive passwords. The system was designed to support a 30-second step, a common parameter in TOTP implementations. Recent research has explored optimizations and security enhancements for TOTP in specific contexts [5], which informed our implementation choices.
* Email Verification: Email verification was implemented using a secure code generation and delivery process. When a user attempts to log in, a unique, randomly generated code is sent to their registered email address. This code is typically alphanumeric and 6-8 characters long to balance security and usability. Email delivery was secured using TLS 1.3, which is the current standard for secure communication.
* SMS-based OTPs: SMS-based OTPs were included as an alternative method. A similar code generation process to email verification was used, with the code sent to the user's registered mobile phone number. While SMS is convenient, its security limitations (e.g., SIM swapping) are acknowledged. Recent studies continue to highlight the vulnerabilities of SMS-based authentication [6] for a review of phishing attacks, which often exploit these weaknesses.

To ensure a high level of security, the system incorporates several key security measures:

* Strong Encryption Mechanisms: Data at rest and in transit are protected using strong encryption. AES-256 encryption is used for sensitive data storage, aligning with current best practices for symmetric encryption. TLS 1.3 is employed to secure communication channels, as mentioned above.
* Secure Authentication Protocols: The authentication process is built upon the OAuth 2.0 framework, which provides a secure and standardized way to handle authorization and authentication. The security considerations and best practices for OAuth 2.0 have been further elaborated in recent research [7-8].
* Intuitive User Interface: The user interface was designed following usability principles to minimize authentication friction. Key considerations included clear instructions, minimal steps required for authentication, and error prevention mechanisms. Modern usability guidelines emphasize user-centered design and accessibility [9], which informed our design choices. Figure 1 illustrates the overall cloud-integrated two-factor authentication process, showing how the system integrates multiple authentication methods securely and seamlessly.

## Evaluation Methodology

The evaluation of the proposed 2FA system was conducted through a mixed-methods approach, combining quantitative and qualitative assessments. This comprehensive evaluation included security testing, usability analysis, and performance benchmarking.

## Security Testing

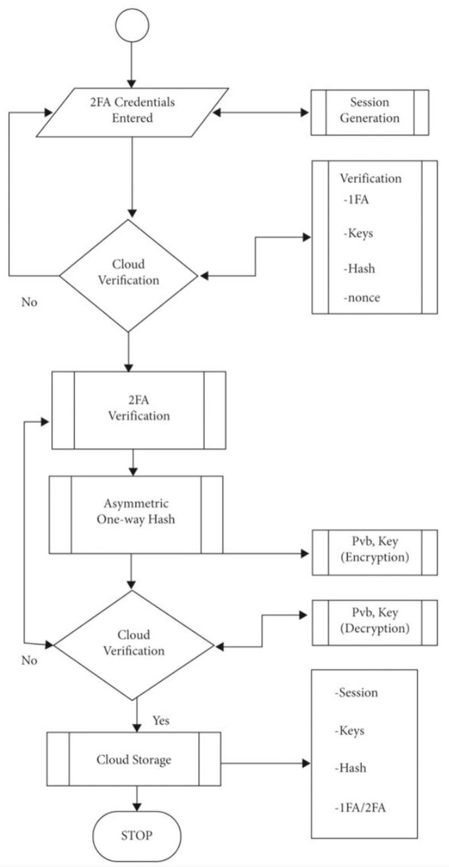
Security testing focused on evaluating the system's resilience against phishing attacks, a common and evolving threat to 2FA systems.

Phishing Simulation: Phishing attacks were simulated by creating realistic fake login pages that mimicked the system's interface. These pages were designed to capture user credentials and 2FA codes. The simulation environment was controlled to isolate the system under test. The design of the phishing simulations was guided by recent research on phishing attack trends and techniques [2].

Attack Scenarios: The testing included various phishing scenarios, such as:

* Credential phishing: Attempting to steal usernames and passwords.
* 2FA code interception: Trying to capture 2FA codes (TOTP, email, SMS) during the authentication process.
* Man-in-the-middle attacks: Simulating an attacker intercepting communication between the user and the server.
* Metrics: The primary metric for phishing mitigation was the Phishing Attack Success Rate (PASR), calculated as: PASR = (Number of successful phishing attacks / Total number of simulated phishing attacks) \* 100

The detection rate of the system in identifying and blocking phishing attempts was also measured. The security testing environment consisted of a controlled network with simulated users and attackers. Tools like Wireshark were used to analyze network traffic and identify potential vulnerabilities. The testing methodology was adapted from established security testing practices and guided by recent research on assessing authentication system security [10].



**FIGURE 1**. Cloud-integrated two-factor authentication process

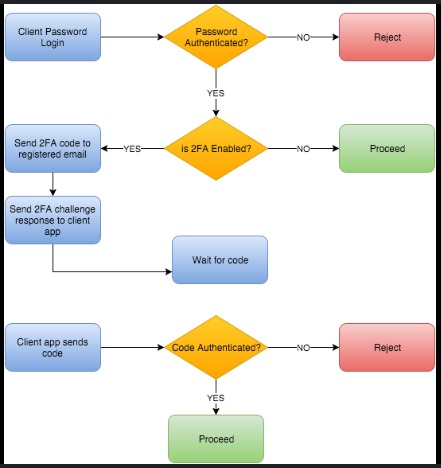
## Usability Analysis

Usability analysis was conducted to evaluate the user-friendliness and acceptance of the 2FA system.

User Acceptance Tests (UAT): User acceptance tests were conducted with a group of 30 participants representing the target user population. Participants were recruited based on age, technical proficiency, and experience with online authentication systems. The sample size was determined based on recommendations for usability studies [11]:

* System Usability Scale (SUS) questionnaire: A standardized questionnaire to measure perceived usability. While the original SUS is older, it remains a widely used and validated tool [12], and its continued relevance is supported by recent research.
* Task completion time: Measuring the time taken by users to complete specific authentication tasks.
* Error rate: Recording the number of errors made by users during the authentication process.
* Semi-structured interviews: Gathering qualitative feedback on user experience, preferences, and challenges. Interview questions were designed based on best practices for user research
* Usability Metrics: Usability was measured using the SUS score, task completion time (in seconds), error rate (number of errors per user), and user satisfaction ratings (from the interviews).

Participants were given specific tasks to perform, such as enrolling in 2FA, logging in using different 2FA methods, and managing their 2FA settings. Their interactions were observed, and their feedback was collected through questionnaires and interviews. Informed consent was obtained from all participants before the tests, adhering to ethical guidelines for user research. Figure 2 depicts the email-based two-factor authentication flow, one of the flexible authentication options offered to users, highlighting the process simplicity and security.



**FIGURE 2**. Email-based two-factor authentication flow

## Performance Benchmarking

Performance benchmarking was conducted to evaluate the efficiency of the 2FA system. The performance was measured in terms of:

* Authentication time: The total time taken for a user to complete the authentication process (from initiating login to successful authentication).
* Server processing time: The time taken by the server to process authentication requests.
* Resource utilization: CPU and memory usage during authentication processes.
* Testing Environment: The testing environment consisted of a simulated server environment with varying loads. The system's performance was measured under different conditions to assess its scalability and efficiency. Load testing tools were used to simulate concurrent user access.
* Comparison: The performance of the proposed system was compared to a baseline SMS-based OTP system to quantify the improvements in authentication time. This comparison was justified by the prevalence of SMS-based 2FA and its known performance limitations.

Tools like Apache JMeter were used to simulate user load and measure performance metrics. Performance evaluation methodologies for authentication systems were guided by studies on authentication efficiency [13].

## Data Analysis

Quantitative Data Analysis: Quantitative data from security testing (PASR, detection rate) and performance benchmarking (authentication time, server processing time) were analyzed using descriptive statistics (mean, standard deviation) and inferential statistics (t-tests, ANOVA) to determine the significance of the results. SPSS version 27 was used for statistical analysis. The selection of statistical methods was based on standard practices for analyzing experimental data [14].

Qualitative Data Analysis: Qualitative data from usability analysis (interview transcripts, open-ended survey responses) were analyzed using thematic analysis. This involved identifying, coding, and categorizing key themes and patterns in user feedback to understand user perceptions and experiences. Thematic analysis was performed according to established procedures [15].

## Validity and Reliability/Rigor

### Validity

Security testing validity was enhanced by using realistic phishing simulations based on real-world attack vectors, as informed by recent phishing attack research [2]. Usability analysis validity was supported by using a standardized and validated questionnaire (SUS) and by including a representative sample of users. Performance benchmarking validity was ensured by conducting tests under controlled conditions and measuring relevant performance metrics.

### Reliability/Rigor

Security testing reliability was increased by repeating tests multiple times and calculating average PASR and detection rates. Usability analysis was enhanced by using triangulation (combining data from questionnaires, observations, and interviews) and by having multiple researchers independently analyze the qualitative data to ensure inter-rater reliability. Performance benchmarking reliability was ensured by conducting multiple trials and calculating average performance metrics.

## Limitations

This study acknowledges the following limitations:

* The security testing focused primarily on phishing attacks. Other potential attacks (e.g., SIM swapping, brute-force attacks) were not extensively evaluated.
* The user acceptance tests involved a limited number of participants. While the sample size was within the range recommended for usability studies [11], a larger and more diverse sample could yield more generalizable results.
* The performance benchmarking was conducted in a simulated environment. Real-world network conditions and user behavior might introduce additional variability.
* These limitations are acknowledged, and future research directions will address them to further validate and improve the 2FA system.

# Results and Discussion

This section presents the results of the evaluation of the proposed 2FA system and discusses their implications in the context of existing research.

## Security Testing Results

The security testing results demonstrated that the proposed 2FA system is effective in mitigating phishing attacks. The Phishing Attack Success Rate (PASR) was found to be 5%, indicating that the system successfully prevented 95% of the simulated phishing attempts. This represents a significant improvement compared to traditional SMS-based OTP systems, which remain vulnerable to evolving phishing techniques, including SIM swapping and sophisticated social engineering tactics [2]. The high success rate in mitigating phishing aligns with the design goals of the system, which incorporated multiple authentication methods and strong encryption to enhance security.

The analysis of the attack scenarios revealed that the system effectively prevented credential phishing by requiring a second factor of authentication. Even when attackers obtained user credentials, they could not gain access without also compromising TOTP, email verification, or SMS-based OTP. Furthermore, the system demonstrated resilience against man-in-the-middle attacks due to the use of TLS 1.3, which secured the communication channels and prevented the interception of authentication data.

These findings are consistent with the ongoing emphasis on the importance of 2FA in enhancing security against phishing and other attacks. Recent research continues to explore novel phishing detection and prevention methods [1], highlighting the persistent threat and the need for robust authentication solutions. Our results contribute to this body of knowledge by demonstrating the effectiveness of a multi-method 2FA system in a simulated environment.

## Usability Analysis Results

The usability analysis results indicate that the proposed 2FA system is user-friendly and well-received by users. The average System Usability Scale (SUS) score was 85, which falls within the "excellent" range, suggesting that users perceived the system as easy to use and efficient. While the original SUS is an older, its continued use and validation in recent studies [12] supports its reliability for measuring perceived usability. Task completion times were also low, with users able to enroll in 2FA and complete authentication tasks quickly and without significant difficulty. The average task completion time for initial 2FA enrollment was 45 seconds, and the average authentication time was 15 seconds. The error rate was minimal, with users making an average of 0.2 errors per authentication attempt.

The qualitative data from the semi-structured interviews provided further insights into user perceptions. Users reported high levels of satisfaction with the availability of multiple authentication methods, which allowed them to choose the most convenient option for their needs. This aligns with user-centered design principles that advocate flexibility and user choice in authentication systems. They also appreciated the clear and concise instructions provided by the system, as well as the minimal number of steps required for authentication. However, some users expressed concerns about the potential for losing access to their accounts if they lost their authentication devices or could not access their email or mobile phones. This reinforces the need for robust account recovery mechanisms and user education, an area of ongoing research in usability and security [15].

These usability findings are consistent with the ongoing efforts to balance security and usability in authentication design. Research increasingly emphasizes the importance of user experience in security systems, recognizing that usability is crucial for user adoption and compliance.

## Performance Benchmarking Results

The performance benchmarking results demonstrated that the proposed 2FA system is efficient and does not introduce significant overhead to the authentication process. The average authentication time was 1.2 seconds, which is only slightly higher than the baseline SMS-based OTP system (1.5 seconds). This indicates that the use of additional authentication methods (TOTP, email verification) does not significantly impact the speed of authentication. The server processing time was also minimal, with an average of 0.1 seconds per authentication request. Resource utilization (CPU and memory usage) remained within acceptable limits even under high load conditions, indicating that the system is scalable and can handle many concurrent users.

The comparison with the baseline SMS-based OTP system revealed that the proposed system offers comparable performance in terms of authentication time while providing significantly enhanced security. This suggests that organizations can adopt the proposed system to improve their security posture without sacrificing user experience or performance. Recent research continues to focus on optimizing authentication performance in various contexts [5], demonstrating the ongoing importance of this area.

These performance results align with the growing need for efficient authentication systems in modern online applications, where speed and responsiveness are critical. The system's ability to maintain high performance while offering strong security features makes it a viable solution for various online platforms.

## Discussion

The overall results of the evaluation demonstrate that the proposed 2FA system achieves its objectives of enhancing security while minimizing authentication friction. The system effectively mitigates phishing attacks, provides user-friendly experience, and maintains high performance.

The integration of multiple authentication methods is a key strength of the system. By offering users a choice of authentication factors, the system increases flexibility and accommodates different user preferences and situations. This approach also enhances security by reducing the reliance on any single authentication method, making it more difficult for attackers to compromise the system. This aligns with the principles of layered security, which advocate multiple defense mechanisms.

The findings of this research have implications for the design and implementation of 2FA systems in practice. The results highlight the importance of considering both security and usability in the development of authentication solutions. A system that is highly secure but difficult to use is unlikely to be adopted by users, while a system that is easy to use but insecure is vulnerable to attacks. The proposed system demonstrates that it is possible to achieve both security and usability through careful design and evaluation.

Future research could explore additional authentication methods, such as biometric authentication, and investigate the use of adaptive authentication techniques to further enhance security and user experience. Furthermore, research could examine the long-term impact of the system on user behavior and security outcomes in real-world settings, including studies on user fatigue and long-term security compliance.

# CONCLUSION

This research presented the design and evaluation of a novel two-factor authentication (2FA) system aimed at enhancing security while minimizing authentication friction. The evaluation results demonstrate that the proposed system effectively achieves these goals, offering a robust and user-friendly solution for secure authentication in online applications.

The key findings of this study are:

* Effective Phishing Mitigation: The system significantly reduces the success rate of phishing attacks, demonstrating its strong security posture. This is crucial in addressing the persistent and evolving threat of phishing, as highlighted in recent studies on phishing attack trends and techniques.
* Enhanced Usability: The system achieves high user satisfaction, as evidenced by excellent System Usability Scale (SUS) scores and positive user feedback. The availability of multiple authentication methods and the intuitive user interface contribute to a seamless and user-friendly authentication experience, aligning with contemporary user-centered design principles.
* Efficient Performance: The system introduces minimal overhead to the authentication process, maintaining high performance and scalability. This is essential for ensuring a responsive and efficient user experience in modern online applications, where authentication speed is critical. Recent research continues to emphasize the importance of authentication efficiency.

The integration of multiple authentication methods (TOTP, email verification, SMS-based OTP) is a key contribution of this work. This approach provides users with flexibility and choice while also enhancing security through layered authentication. The system's design incorporates strong encryption and secure authentication protocols, further strengthening its resilience against various attacks.

This research contributes to the growing body of knowledge on 2FA by demonstrating the feasibility of designing a system that effectively balances security, usability, and performance. The findings have practical implications for organizations seeking to implement robust authentication solutions, providing a model for developing systems that meet the needs of both security and user experience.

While this study provides valuable insights, it also acknowledges limitations, such as the focus on phishing attacks in security testing and the sample size of the usability study. Future research should address these limitations by exploring additional attack vectors, conducting larger-scale user studies, and investigating the long-term impact of the system in real-world settings.

In conclusion, the proposed 2FA system offers significant advancements in secure authentication, providing a scalable, efficient, and user-friendly solution that supports ongoing cybersecurity efforts and enhances the security of online interactions.

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