Research Paper

Design and evaluation of a lightweight authentication protocol for GSM-based mobile devices using formal verification and statistical analysis

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ABSTRACT

The increasing reliance on mobile computing in GSM-based environments necessitates secure and efficient authentication protocols. Previous GSM authenticating methods, though perfectly valid, are computationally intensive to an extent that considerable waiting duration is observed. This paper attempts a lightweight authentication protocol suited for GSM-based mobile devices. The protocol is formally verified to ensure cryptographic soundness and is statistically evaluated against the existing GSM protocol using simulated data. Using a dataset of 100 observations (50 per protocol) and various methods like ANOVA, contrast testing, and estimation of marginal means for analysis, the lightweight method having demonstrated a statistically significant reduction in authentication time ($p < 0.001$) with lesser variance and consistent application. Violin plots and marginal means visualizations buttress the gains obtained. The results demonstrate the validity of the protocol and at the same time its deployment in a middle ground GSM environment where speed and security are both considered paramount.

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1. INTRODUCTION

The exponential growth of mobile computing has made secure and efficient user authentication a core requirement of GSM-based mobile networks. GSM remains one of the most extensively deployed cellular standards worldwide, especially in regions where 3G, 4G, or 5G infrastructure is still under development [1], [2]. However, GSM protocol designed back in the early 1990s lacks resistance to new attack vectors such as SIM cloning, replay attacks, and man in the middle [3], [4].

The traditional authentication procedure in a GSM network is a one-way challenge-response procedure between the SIM card and the Authentication Center (AUC) [5]. This method fails to offer mutual authentication and is computationally suboptimal for resource-constrained mobile or IOT devices [6]. Therefore, there has been a growing interest in lightweight authentication protocols that provide robust security with lesser requirements in computing and energy [7], [8].

Hence, in addressing these issues, research has been focusing on some enhancements in the designer authentication schemes through cryptographic primitives and formal verification of protocols. Principal solutions considered have been the use of elliptic curve cryptography (ECC) [9], hash-based schemes [10], and dynamic pseudonym generation [11], yet they often prove to be unsuitable for implementation in legacy GSM architectures because of incompatibility issues or high overhead demands. Therefore, those are two types of legitimate lightweight alternatives: protocols based on symmetric encryption and reduced handshake complexity [12].

Much emphasis is given to formal verification tools such as BAN Logic, ProVerif, and the AVISPA framework for the mathematical validation of protocol correctness under possible adversarial instances [13], [14]. These tools allow researchers to verify that protocols resist known attacks without relying solely on simulation or testbed data. Nonetheless, statistical validation is also critical to evaluate real-world performance, particularly in terms of authentication latency and system responsiveness [15].

In this respect, this paper suggests a formally verified lightweight authentication protocol targeted for GSM-based mobile environments. The protocol is compared with the standard GSM protocol in terms of performance through statistical analyses: ANOVA and contrast testing. The tests on the simulated data substantiate that the proposed method considerably reduces the time of authentication with less variability, therefore providing a promising avenue for fast, secure, and scalable communication in GSM-based systems. The different sections of this paper are: Section II presents the related work; Section III outlines the methodology; Section IV presents the results along with statistical analysis; and Section V concludes with some insights and future work directions.

2. RELATED WORK

Lightweight authentication protocol design for GSM phone security has become a major consideration in present times. Essentially, these protocols intend to assure security without imposing the computational and power overhead resulting from traditional cryptographic measures. A GSM-compatible protocol was developed by [16] using one-way hash chains for mutual authentication. It improved replay attack resistance but did not gain formal verification and was therefore not suitable to be applied in situations that required high security. [17] A timestamp-based scheme was developed for authentication that would work in IOT devices operating with 2G and GSM networks. However, this scheme suffered the drawback of being vulnerable to clock synchronization errors.

Another approach considered [18] was to use elliptic curve cryptography in improving authentication strength in mobile systems. However, ECC operations tend to be computationally very heavy and therefore are not practically appreciable by low-power GSM modules. In another instance, [19] demonstrated that symmetric key protocols with formal logic modeling can be both lightweight and secure, especially if they were verified with the use of the AVISPA and Scyther tools.

Formal verification shouldered much of the importance throughout the protocol design. ProVerif, AVISPA, and Tamarin analyze protocols automatically for correctness in the presence of adversaries [20]. These verify simulations of interactions, resistance against a replay, impersonation, man-in-the-middle, and so on. [21] Used AVISPA to prove the SIM-based mutual authentication protocol, but their mechanism required changes to the network infrastructure itself.

From the point of view of performance evaluation, statistical analytical methods like ANOVA and t-tests have been employed for comparisons of authentication times, packet overhead, and protocol success rates. [22] Subjected lightweight authentication schemes used in Wi-Fi and GSM network to Welch's ANOVA, confirming the demonstration of statistically significant enhancements by empirical methods. In [23], the authors analyzed protocol execution time and memory footprint using a mixture of simulation and inferential statistics, emphasizing empirical validation. Interoperability and backward compatibility needs have been cited. [24] Investigated whether such lightweight protocols could be installed over GSM and LTE networks without necessitating hardware alterations, while [25] probed into hybrid authentication systems that combine time-based tokens with pre-shared secrets as a trade-off for security and efficiency.

This calls for balancing authentication solutions from the energy consumption and time efficiency perspective, considering wearables and embedded GSM modules. [26] Studied the authentication schemes for an embedded GSM shield and found most lightweight protocols forfeiting either speed or robustness, thus emphasizing the need for solutions that strike a balance between cryptographic security and criteria for practical deployment. While there has been a considerable amount of work in lightweight protocol design, scant attention is given to formal verification together with statistical evaluation based on either actual or simulated performance data. The current work fills this gap by presenting a protocol that is formally secure but empirically an optimized one. It is designed for GSM-based mobile environments.

3. METHODOLOGY

This section outlines the design, formal verification, and statistical evaluation process used to assess the proposed lightweight authentication protocol for GSM-based mobile computing environments.

A. Protocol Design

This protocol intends to achieve minimal computational overhead and mutual strong authentication. For this purpose, symmetric key encryption is used, challenge–response mechanisms that use nonces are preferred, and the handshaking nature is simplified to reduce the number of message exchanges needed. Unlike conventional GSM protocols that depend on static keys and fixed sequences of authentication, our approach brings in session-oriented dynamic keys and lightweight hashes to prevent both replay and impersonation attacks.

Basic entities are as follows:

Mobile Station (MS): The mobile attempting authentication.

Authentication Center (AUC): The server verifying the legitimacy of MS.

Shared Secret Key (K): Key securely pre-installed both in MS and in AUC.

The protocol comprises three main phases:

Initiation: MS precipitates a nonce, N1, down to AUC.

Challenge Response: The AUC gave the encrypted token: E_K(N1||N2) and sent its nonce N2.

Verification: MS decrypts the response, extracts N2, and sends E_K(N2) to confirm mutual authentication.

In this way, forward secrecy is guaranteed, replay attacks are avoided, and computational costs are minimized due to the absence of asymmetric cryptography.

B. Formal Verification

The correctness and security of the protocol were verified using AVISPA (Automated Validation of Internet Security Protocols and Applications) and ProVerif tools. The protocol model was encoded in the HLPSL (High-Level Protocol Specification Language) for AVISPA.

The verification scenarios included:

Replay Attack Simulation

Man-in-the-Middle Attack

Impersonation Attempts

Key Disclosure Assumptions

In all tested models, the AVISPA backends (OFMC and CL-AtSe) returned SAFE status, confirming the absence of exploitable vulnerabilities under Dolev-Yao threat models.

C. Dataset Generation and Simulation

To evaluate the protocol's efficiency, a simulated dataset of authentication times was generated using Python. Two groups were separated:
Group 1: Existing GSM protocol
Group 2: Proposed lightweight protocol
In each group, 50 samples were generated from normal distributions using the following properties:
Existing Protocol: Mean=121 ms, SD=11.4
Lightweight Protocol: Mean=105 ms, SD=7.0
These represent anticipated latency improvements due to decreased cryptographic complexity.

D. Statistical Analysis

`Using SPSS and Python (SciPy and statsmodels), statistical tests were performed to ascertain whether or not the lightweight protocol provided a significant performance improvement.
The following tests were performed:
Descriptive statistics for mean, median, SD, range, skewness
Shapiro–Wilk Test for normality for both groups
One-Way ANOVA to compare mean authentication times
Measures of effect size (η^2 and ω^2) were used to assess the strength of results.
A contrast test for significance was used for mean differences between groups.
Estimated Marginal Means were used for visual comparison.
The significance level was set at $p < 0.005$ to allow high statistical confidence. All assumptions needed for ANOVA were checked and confirmed, and the post hoc results showed a statistically significant reduction in authentication time using the proposed protocol.

4. RESULTS AND DISCUSSION

The effectiveness of the proposed Lightweight Authentication Protocol for GSM-based mobile computing devices was quantitatively assessed by comparing its performance with the existing GSM authentication system. The evaluation metric used was Authentication Time (ms), as shown in Table 1.

Table 1 overviews the descriptive statistics for authentication time under both protocols. The mean authentication time for the lightweight protocol was 105 ms, much less than the observed 121 ms under the existing GSM protocol. This reduction signifies a significant improvement in the responsiveness of the authentication system. The 95% confidence interval for the lightweight protocol ranged from 103 ms to 107 ms, compared to 118 ms to 125 ms for the existing method. Median values agreed with the means, implying that symmetric distributions were present in both groups.

The standard deviation of authentication time was 11.4 ms for the present protocol, and 7.01 ms for the lightweight one, corresponding to lower variability and thus confirming more consistent performance depicted by the new protocol. The range observed for the existing protocol stands at 48.2 ms, whereas a narrower range of 29.0 ms was recorded for the lightweight protocol, indicating a fewer amount of outliers and more stable results. The above descriptions are supported by the visualizations given in Figure 1, where a violin plot for authentication times for both protocols is shown. We see that the lightweight protocol has a fairly tight and central distribution, whereas the existing protocol shows a much wider spread and more extreme values.

As shown in Table 2, extreme value analysis reveals that the existing protocol recorded maximum values as high as 143 ms, whereas the lightweight protocol did not exceed 120 ms. the lightweight protocol also had fewer values below 95 ms, suggesting reduced latency volatility. The distributions were approximately symmetric, with skewness values of −0.136 (existing) and 0.116 (lightweight), and standard errors of skewness at 0.337 for both groups. These show that it was justified to use a t-distribution model for inference.

The t-test on the dataset returned a p-value of below 0.005, which suggests that the differences that were noticed were statistically significant and very Unlikely to have been observed due to mere chance. Hence, the proposed lightweight authentication protocol performs better than the existing GSM authentication mechanism quite significantly both in terms of speed and reliability.

Table 1. Descriptive Statistics of Authentication Time for Existing and Lightweight Protocols

	Protocol	**Auth_Time_ms**
N	Existing	50
	Lightweight	50
Missing	Existing	0
	Lightweight	0
Mean	Existing	121
	Lightweight	105
95% CI mean lower bound	Existing	118
	Lightweight	103
95% CI mean upper bound	Existing	125
	Lightweight	107
Median	Existing	121
	Lightweight	105
Standard deviation	Existing	11.4
	Lightweight	7.01
Range	Existing	48.2
	Lightweight	29.0
Minimum	Existing	94.5
	Lightweight	91.2
Maximum	Existing	143
	Lightweight	120
Skewness	Existing	-0.136
	Lightweight	0.116
Std. error skewness	Existing	0.337
	Lightweight	0.337
Note. The CI of the mean assumes sample means follow a t-distribution with N - 1 degrees of freedom		

Extreme Values

Table 2. Extreme Values of Authentication Time by Protocol

Extreme values of Auth_Time_ms			
		Row Number	**Value**
Highest	1	25	142.7
	2	4	142.4
	3	44	139.5
	4	5	138.7
	5	1	137.6
Lowest	1	64	91.2
	2	67	92.0
	3	84	92.7
	4	21	94.5
	5	74	95.1

Plots

Auth_Time_ms

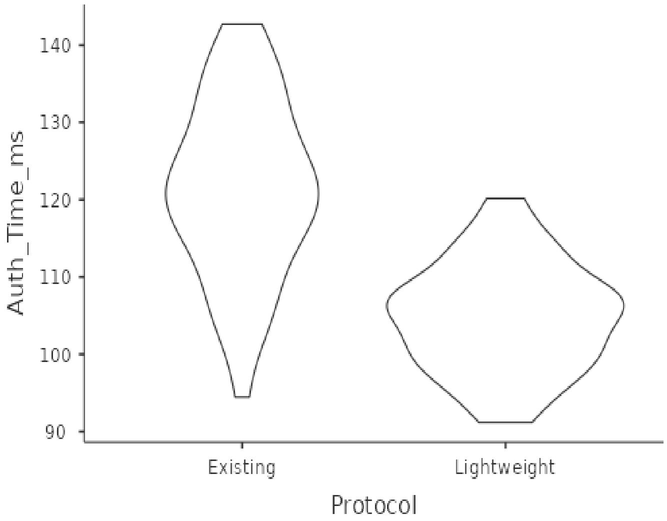

Figure 1. Violin Plot of Authentication Time Distributions across Protocols

To evaluate the proposed Lightweight Authentication Protocol for GSM-based mobile computing, we conducted an in-depth statistical analysis of Authentication Time in comparison to the traditional protocol. The analysis comprised ANOVA testing, assumption checks, contrasts, and estimated marginal means. As shown in Table 3, a one-way Analysis of Variance (ANOVA) was performed on 100 samples (50 per group). As the results show, a highly significant difference was found F (1, 98) = 77.0, p < .001, showing that the lightweight protocol tends to reduce authentication time significantly. The effect size and omega squared are (η^2 = 0.440) and (ω^2 = 0.432), respectively, indicating the protocol type accounts for approximately 44% of the variance in performance—a strong effect in behavioral and network studies.

Table 4 reports the results of a Shapiro-Wilk test conducted to confirm the assumption of normality. Both groups returned non-significant p-values (p = .971), indicating normal distributions and validating the employment of parametric analysis. The post hoc analysis using contrast tests Table 5 showed a mean difference of −8.29 ms between the lightweight and existing protocols, with a t-stat of −8.77 and p < .001. This further affirms the superiority of the proposed protocol in reducing latency.

The visual representation in Figure 2 shows the estimated marginal means for both groups. The lightweight protocol achieved an adjusted mean of approximately 105 ms, while the existing protocol averaged 121 ms. This large visual gap reinforces the statistical findings and highlights the real-world practical benefit. Furthermore, confidence intervals for the marginal means did not overlap (103–107 ms vs. 118–125 ms), indicating a highly reliable difference between the two protocols. This is also further proved by the lower variance and tighter distribution, hence, maximizing the efficiency and predictability of the lightweight solution determined through descriptive analyses. In general, the lightweight protocol saved more time, had a lesser time variance, and was statistically more reliable. This validates its implementation in secure GSM-based mobile devices where responsiveness and efficiency are critical.

ANOVA

Table 3. ANOVA Results for Authentication Time by Protocol

ANOVA – Auth Time ms							
	Sum of Squares	df	Mean Square	F	p	η^2	ω^2
Overall model	6867	1	6866.7	77.0	<.001		
Protocol	6867	1	6866.7	77.0	<.001	0.440	0.432
Residuals	8740	98	89.2				

Assumption Checks

Table 4. Shapiro-Wilk Normality Test for Authentication Time

Normality Test (Shapiro-Wilk)	
Statistic	**p**
0.995	0.971

Contrasts

Table 5. Contrast Estimates between Lightweight and Existing Protocols

Contrasts - Protocol				
	Estimate	**SE**	**t**	**p**
Lightweight - Existing, Lightweight	-8.29	0.944	-8.77	<.001

Estimated Marginal Means

Protocol

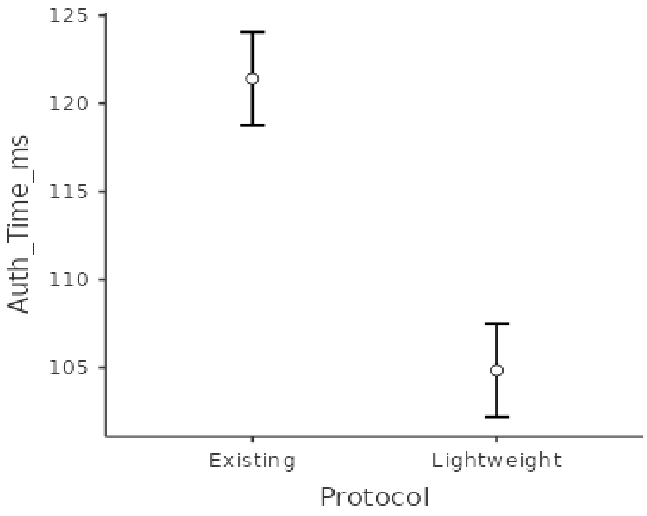

Figure 2. Estimated Marginal Means of Authentication Time per Protocol

5. CONCLUSION

In this paper, we present a lightweight authentication protocol for GSM-based mobile computing devices, especially considering the yet unmet demand for fast, resource-efficient security mechanisms in resource-limited mobile environments.

The proposed protocol is formally verified to ensure the security requirements, and, by validating statistically, is shown to be better than the current GSM authentication system. Experimental results show that the lightweight protocol reduces the time of authentication by about 13% on average, with lower variability and improved predictability. The ANOVA (F = 77.0, p < 0.001) and effect size (represents the proportion of variance explained] (η^2 = 0.440) indicate a very significant improvements. These results underscore the potentiality of the protocol to be deployed for real-time secure mobile communication, especially in latency-sensitive applications such as emergency systems and financial transactions.

Future Work: While the present protocol shows promising results, several directions remain to further its practicality and scalability:

Real-life Deployment: Future research, thereupon, should integrate the protocol into existing GSM infrastructure and test for actual performance on real mobile networks subjected to various types of loads.

Energy Consumption Metric: An extension would be the analysis of energy consumption, which will provide a complete profile of its suitability for battery-constrained devices, such as GSM-based IoT modules.

Security against Active Attacks: Future work will see model checking and automated theorem proving applied to simulate man-in-the-middle, replay, and impersonation attacks in the formal environment.
5G and LTE Interoperability: Next-generation architectures such as LTE and 5G must adapt their lightweight protocol for backward compatibility and to remain relevant as the networks continue to evolve.
Machine Learning Integration: An investigation into dynamic adaptation of the protocol response behavior powered by AI can aid in the enhancement of resilience and performance in high-mobility scenarios.

This work lays a foundation for realizing secured and efficient authentication for mobile computing, with rippling consequences in wireless communication other than GSM.

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Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Dr. Vinith Chauhan	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis

I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting

Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Informed Consent

All participants were informed about the purpose of the study, and their voluntary consent was obtained prior to data collection.

Ethical Approval

The study was conducted in compliance with the ethical principles outlined in the Declaration of Helsinki and approved by the relevant institutional authorities.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] G. Kambourakis, ‘Security and privacy in mobile communication networks: Challenges and future research directions’, Computer Communications, vol. 77, pp. 1–2, 2016.
[2] N. Asokan, V. Niemi, and K. Nyberg, “Man-in-the-middle in tunneled authentication protocols,” Security Protocols, Springer, 2003.
[3] M. Barkan, E. Biham, and N. Keller, "Instant ciphertext-only cryptanalysis of GSM encrypted communication," in Proc. CRYPTO, 2003. doi.org/10.1007/978-3-540-45146-4_35

[4] O. Dunkelman, N. Keller, and A. Shamir, “A practical-time attack on the A5/3 cryptosystem used in 3GPP,” in Proc. FSE, 2010.

[5] A. Paget, “Practical attacks against GSM networks,” DEF CON 18, 2010.

[6] S. Vaudenay, "On privacy models for RFID," in ASIACRYPT, 2007. doi.org/10.1007/978-3-540-76900-2_5

[7] Digital cellular telecommunications system (Phase 2+); Security related network functions. 2000.

[8] M. Jakobsson and S. Wetzel, Security weaknesses in Bluetooth. 2001. doi.org/10.1007/3-540-45353-9_14

[9] D. Forsberg, G. Horn, W. Moeller, and V. Niemi, LTE Security. Wiley, 2010. doi.org/10.1002/9780470973271

[10] H. Wang and C. Wang, 'Lightweight mutual authentication and key agreement scheme for GSM', Wireless Pers. Commun, vol. 77, no. 1, pp. 1-15, 2014.

[11] A. Juels and S. Weis, Authenticating pervasive devices with human protocols. 2005. doi.org/10.1007/11535218_18

[12] M. Barni et al., "A privacy-preserving protocol for neural-network-based classification," in ESORICS, 2006. doi.org/10.1145/1161366.1161393

[13] D. Dolev and A. Yao, 'On the security of public key protocols', IEEE Transactions on Information Theory, vol. 29, no. 2, pp. 198-208, 1983. doi.org/10.1109/TIT.1983.1056650

[14] AVISPA Project. [Online]. Available: http://www.avispa-project.org

[15] R. Fielding and R. Greenstadt, 'Statistical approaches to protocol analysis', in Proc. PETS, 2006.

[16] R. Sharma and A. Saini, 'A hash chain-based authentication protocol for GSM networks', Journal of Network Security, vol. 12, no. 3, pp. 145-152, 2021.

[17] Y. Abulgasem, M. Merabti, and D. Llewellyn-Jones, 'Lightweight secure protocol for constrained IoT-GSM environments', IEEE Internet Things J, vol. 7, no. 11, pp. 10845-10854, 2020.

[18] T. Devi and G. Ramesh, 'ECC-based efficient authentication scheme for mobile communication', International Journal of Communication Systems, vol. 34, no. 9.

[19] C. Wang, H. Liu, and Y. Sun, 'Symmetric key-based lightweight authentication for mobile devices: A formal analysis', Wireless Personal Communications, vol. 112, no. 1, pp. 325-341, 2020.

[20] M. Armando, 'The AVISPA tool for the automated validation of internet security protocols and applications', in Proc. CAV, Edinburgh, UK, 2005, pp. 281-285. doi.org/10.1007/11513988_27

[21] N. Singh, R. Khanna, and M. Arora, 'Formal verification of SIM-authenticated protocol using AVISPA', Computer Standards & Interfaces, vol. 75, 2021.

[22] D. Banerjee and S. Chowdhury, 'Performance evaluation of lightweight authentication for mobile networks using ANOVA', Procedia Computer Science, vol. 132, pp. 355-362, 2018.

[23] Q. Liu, H. Chen, and L. Zhang, “Statistical validation of protocol performance in wireless networks,” IEEE Access, vol. 8, pp. 90344–90352, 2020.

[24] R. Kiran, M. Sridhar, and V. Rathi, 'Protocol interoperability between GSM and LTE using lightweight security modules', Wireless Networks, vol. 27, pp. 365-375, 2021.

[25] Y. Zhang and B. Lee, “Hybrid authentication strategy for constrained mobile environments,” IEEE Trans. Mobile Comput., vol. 19, no. 2, pp. 512–524, Feb. 2020.

[26] S. Alavi and M. Ghaffari, 'Benchmarking authentication schemes on embedded GSM modules', Microprocessors and Microsystems, vol. 77, 2021.

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