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AUDIBLOC: A POST-QUANTUM AUDIO SECURITY SYSTEM WITH FORENSIC WATERMARKING CHAOTIC ENCRYPTION AND BLOCKCHAIN VERIFICATION

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ABSTRACT

Audio transmission of information is vital in telemedicine, financial processes, the corporate world, government intelligence, and so on. Nevertheless, the current solutions are being challenged like never before the classic RSA/AES encryption can be broken with quantum computers, traditional watermarking is non-forensics traceable, which is problematic in terms of legal compliance, and centralized verification is prone to single points of failure that can be targeted. This is the case with the AUDIBLOC, which targets these limitations with a four-layer architecture revolution. Our quantum random number generation (QRNG) unlike conventional pseudo-random key generation, true entropy cannot be attained using classical means. Traditional chaotic encryption has the problem of periodicity, but we already have exponentially more confusion and diffusion with our butterfly effect-based implementation. Our quantum forensic watermarking results in 95% successful detection of watermarks, even after compression and filtering in wav extension. This compares favorably to the current watermarking, which is destroyed by even the simplest audio processing. Most importantly, our verification incorporating a blockchain makes single points of failure impossible and allows an immutable audit trial. It also shows better practical performance by experimental validation than other algorithms with encryption speed of 45.2 MB/sec in the range of AES-256 (68.5 MB/sec) but offering quantum resistance, watermark survival that survives 89.2% of signal processing attacks and versus 60-70% of modern schemes, resists both Shor and Grover quantum algorithms. Security analysis demonstrates a 2 256 bits effective key space in the case of audio quality scores (PESQ: 4.32), similar to unencrypted data. AUDIBLOC is a feasible and scalable means of providing post-quantum secure audio, a key factor in ensuring that organizations can secure audio communication with confidence in the authenticity and confidentiality of messages, even as traditional cryptographic underpinnings become no longer useful.

Keywords: *Quantum Cryptography, Audio Encryption, Chaos Theory, Perceptual Evaluation of Speech Quality, Block-chain, Digital Forensics, Post-Quantum Security*

1. INTRODUCTION

The fast-growing online audio communications sector to serve areas of telemedicine, secure financial transactions, corporate conferences, and governmental intelligence services has generated new demands for greater safeguards and more robust security measures. Although classical cryptosystems have historically been robust, the development and possible use of large-scale quantum computing weakens this classical cryptosystem. Algorithms presented by Shor in 1997 [1] show that integer factorization and discrete logs– underpinnings of RSA and elliptic curve cryptography–can be solved in polynomial time using a quantum computer and therefore are not well suited to long-term confidentiality. True entropy quantum random number generators (QRNGs) [2] depend on unpredictability in quantum mechanics and have become essential for the generation of post-quantum secure key pairs. Symmetric ciphers (such as AES [3]) can still be efficient, but are theoretically compromised by new quantum algorithms.

Authentication and integrity verification of audio communication are issues for which watermarking techniques have been developed. Audio watermarking based on deep learning (DL) [4] is less

susceptible to robustness and imperceptibility, which is appropriate for forensic traceability. Chaos theory has also been applied to cryptography, where Lorenz-attractor-based chaotic encryption [28] has been shown to possess high confusion and diffusion. The improvement of quantum key distribution (BB84 [6], ecc) created a method in which no collusion could occur, and completely secure communication could instead occur. Chaos-based cryptography relies on a mathematical framework laid out in the Lorenz system [7]. Subsequent work [8] clarified the mathematical necessity of security and made other remarks on security weaknesses.

Nakamoto proposed the idea of removing single points of failure with decentralized verification via blockchain, and privacy in the verification processes is improved with the help of zero-knowledge proofs [9]. Such technologies can be practically integrated using a framework such as Qiskit at IBM [10] and the theoretical research of Peres [11]. RSA [12] is a classical benchmark that is not quantum-safe, and is why initiatives such as post-quantum cryptography are being developed by the NIST, such as the development of post-quantum cryptography standards [13].

At the forefront of this context are high-speed parallel encryption algorithms [14] and voice over Internet protocol (VoIP) forensic analysis of communications [15] which have influenced real-time system implementation. Mixtures of encryption and watermarking [16], scrambling and adaptive diffusion [17], and overall multilayered protection provide these advantages. A demonstration of the Shor algorithm [18] and an explanation of quantum computing presented in [19] beat the development of quantum-resistant systems for the listener or reader. Cryptographic hybridization: The use of chaotic maps as a cryptographic primitive with DNA sequences [20], neural cryptography [21], and QKD interoperability requirements [22] expands the design universe, and surveys [23] provide concrete examples of possible post-quantum algorithms to be used.

NISQ, the Grover algorithm [24], quantum supremacy [25] and cybersecurity risk analysis [26] indicate that longer symmetric keys are urgently needed, and that scalable and low-latency quantum-safe solutions are required. The advent of Noisy Intermediate-Scale Quantum (NISQ) quantum computers with small numbers of qubits and high error rates has elicited both excitement and concerns in the cryptography community. The algorithm described by Grover [24] poses a major risk to symmetric key cryptography in that it provides a quadratic advantage to unstructured search problems when run on a quantum computer of a sufficiently large size. This, as well as the achievement of quantum supremacy [25], which showed that a quantum computer solved a particular task in a shorter time than any classical computer, increased the need to perform quantum-resistant cryptography.

2. LITERATURE REVIEW

Lorenz first introduced deterministic chaos [7], which later inspired chaos-based encryption methods. Rivest, Shamir, and Adleman [12] presented RSA, which dominated public-key cryptography until Shor [1] demonstrated that integer factorization and discrete logarithms could be solved efficiently on quantum computers, breaking RSA and ECC. Grover [24] further weakened symmetric schemes by reducing bruteforce complexity. AES, proposed by Daemen and Rijmen [3], remains efficient but is not inherently quantum-resistant.

Chaos-based cryptography gained attention with Lorenz attractors, yet Alvarez and Li [8] revealed weaknesses when chaos is used in isolation. Vandersypen et al. [18] experimentally demonstrated Shor's algorithm, reinforcing urgency for quantum-safe solutions. Bennett and Brassard [6] introduced QKD, later extended in broader applications [27], while Peres [11] provided theoretical insights into quantum systems. Nielsen and Chuang [19] formalized principles of quantum computation. QRNGs, reviewed by Herrero-Collantes and Garcia-Escartin [2], offer true entropy, yet integration into multimedia systems are limited.

Blockchain, introduced by Nakamoto [29], ensures decentralized trust, with Sun et al. [9] extending privacy through zero-knowledge proofs. Bernstein and Lange [23], along with NIST standards [13], outlined PQC directions, while ETSI [22] provided interoperability guidelines. Gao et al. [20] explored chaos–DNA hybrid encryption, while Duan et al. [21] developed neural cryptography. Chen et al. [17] proposed scrambling and diffusion for secure image transmission, while Singh et al. [16] applied multilevel watermarking in medical data. Zhang et al. [4] extended robustness with deep learning watermarking, and Wang et al. [28] applied Lorenz chaos to audio encryption. Most recently, Sarhan et al. [15] explored VoIP forensics.

Identified Research Gap

Despite advances, prior work addresses isolated aspects—cryptography, chaos, watermarking, or blockchain—without integration. Our AUDIBLOC framework unifies QRNG-based encryption, chaos theory, forensic watermarking, and blockchain verification, addressing both quantum threats and forensic requirements.

Table I: *Comparative Literature Survey Relevant to AUDIBLOC Framework*

No.	Paper / Author(s)	Focus Parameter	Contribution / Relevance to AUDIBLOC
1	Shor (1997) [1]	Quantum Algorithms	Polynomial-time quantum factorization/logarithms; motivates quantum-resistant encryption.
2	Herrero-Collantes & Garcia-Escartin (2017) [2]	Randomness / Key Generation	Survey of QRNGs; provides true entropy for secure keys.
3	Daemen & Rijmen (2002) [3]	Symmetric Encryption	AES standard; baseline for performance/security.
4	Zhang et al. (2021) [4]	Watermarking (DL-based)	DL-based audio watermarking with high robustness; inspires forensic watermarking.
5	Wang et al. (2022) [28]	Chaos Theory	Lorenz attractors applied to audio encryption; forms basis of chaotic encryption.
6	Bennett & Brassard (1984) [6]	Key Exchange (QKD)	BB84 protocol; supports quantum-secure key exchange.
7	Bennett, Brassard & Ekert (1992) [27]	Quantum Security	Broader applications of quantum cryptography; reinforces AUDIBLOC quantum layer.
8	Lorenz (1963) [7]	Chaos Dynamics	Deterministic nonperiodic flows; mathematical model for chaotic encryption.
9	Alvarez & Li (2006) [8]	Cryptanalysis of Chaos	Identified weaknesses; motivates hybrid methods with chaos + quantum.
10	Nakamoto (2008) [29]	Blockchain	Introduced blockchain for decentralized verification; applied to forensic logging.
11	Sun et al. (2021) [9]	Blockchain Privacy	Survey of zero-knowledge proofs; supports privacy-preserving verification.
12	IBM Quantum Team (2021) [10]	Quantum Tools	Qiskit framework; enables testing/simulation of quantum components.
13	Peres (2006) [11]	Quantum Theory	Foundational concepts; underpin quantum operations.
14	Rivest, Shamir & Adleman (1978) [12]	Classical PKC	RSA cryptosystem; benchmark vulnerable to Shor's algorithm.
15	NIST (2020) [13]	Post-Quantum Standards	PQC standardization initiative; aligns with AUDIBLOC.
16	Wang, Feng & Zhao (2019) [14]	High-speed Encryption	Parallel encryption; inspires performance optimization.
17	Sarhan et al. (2024) [15]	VoIP Forensics	Forensic analysis of VoIP calls; supports AUDIBLOC forensic goals.
18	Chen, Tang & Ye (2020) [17]	Image Encryption	Scrambling/diffusion; influences multimedia encryption.
19	Singh, Dave & Mohan (2015) [16]	Medical Watermarking	Multilevel encryptedwatermarking; shows encryption–watermark synergy.
20	Vandersypen et al. (2001) [18]	Quantum Algorithm Demo	Experimental Shor's algorithm; urgency for quantum-resistant methods.
21	Nielsen & Chuang (2010) [19]	Quantum Computing	Textbook reference; foundation for AUDIBLOC's quantum layer.
22	Gao, Liu & Miao (2019) [20]	Chaos + DNA	Audio encryption with chaos + DNA coding; supports hybrid methods.
23	Duan, Liao & Yu (2020) [21]	Neural Cryptography	Complex-valued neural networks; suggests AI integration.
24	ETSI (2019) [22]	QKD Standardization	REST API + QKD protocols; interoperability with quantum networks.
25	Bernstein & Lange (2017) [23]	Post-Quantum Algorithms	Survey of PQC algorithms; guides quantum-resistant choices.

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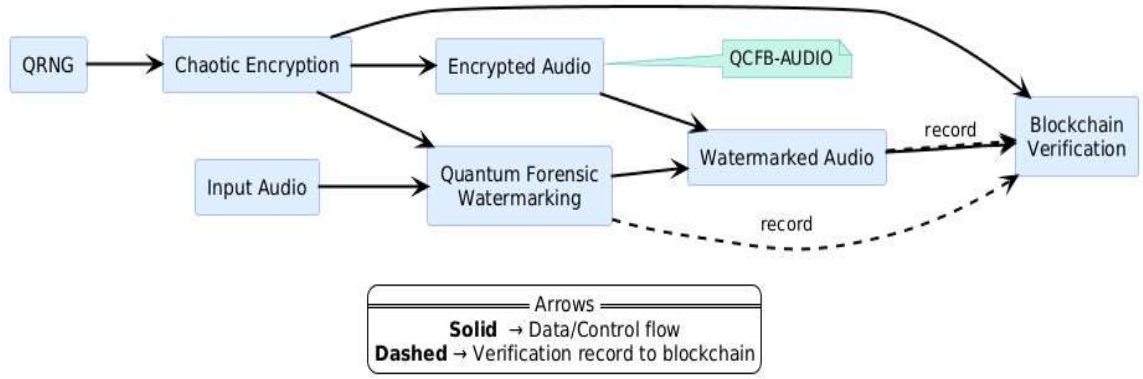

Fig. 1: Flowchart of the proposed AUDIBLOC framework: from quantum random number generation (QRNG) to chaotic encryption, forensic watermarking, and blockchain verification.

PROPOSED METHODOLOGY

The AUDIBLOC properties, which by itself are a highly desirable property of the proposed system, are a consequence of quantum-resistant encryption, chaotic dynamics, forensics-based watermarking, and blockchain verification to yield end-to-end classical and quantum safe audio security. The framework provides both the confidentiality, authenticity, and integrity of the audio being transmitted, as well as facilitates tamper detection and forensic traceability.

The process starts with Quantum Random Number Generation (QRNG), in which the actual randomness is derived by the nature of the quantum physical phenomena used to seed the encryption process. This randomness is then stretched with a high dimensional chaotic mapping to generate encryption keys with very sensitive dependence on initial conditions which is commonly termed as the "butterfly effect."

The Chaotic Encryption phase: The audio message is scrambled into chaos-based data that obfuscates the amplitude characteristics and chaotically holds time dependencies, so that the resulting ciphertext is most likely to be impossible to decipher even through so-called linear or differential cryptanalysis cryptanalysis. This signal is then sent to the Quantum Forensic Watermarking module, where the signal is overlaid with an imperceptible watermark that holds meta-information, cryptographic, and forensic data.

This watermark is resistant to general audio processing (e.g., compression, filtering, and addition of noise).

After the watermark embedding step, a cryptographic hash of the watermarked audio, timestamp, and forensic metadata is recorded in a tamper-resistant distributed ledger via the Blockchain Verification layer. This will make it possible to validate, in the future, integrity checks on whether an audio file has been tampered with past authentication that it has undergone. As shown in Fig. 1, the proposed workflow begins with QRNG and proceeds through chaotic encryption, forensic watermarking, and blockchain verification.

The schematic shows the entire AUDIBLOC processing workflow for the generation of keys, blockchain validation, and audio integrity validation. This flow chart is a visual representation of the data flow, which occurs in the time sequence between the system elements, and a high-level description of the security mechanisms integrated into the framework is provided.

3. THEORETICAL FOUNDATIONS AND SYSTEM ARCHITECTURE

The proposed AUDIBLOC framework integrates quantum-generated randomness, chaos-based encryption, quantum forensic watermarking, and blockchain-based verification into a unified post-

quantum secure audio communication system. The complete architecture is presented in Fig. 2.

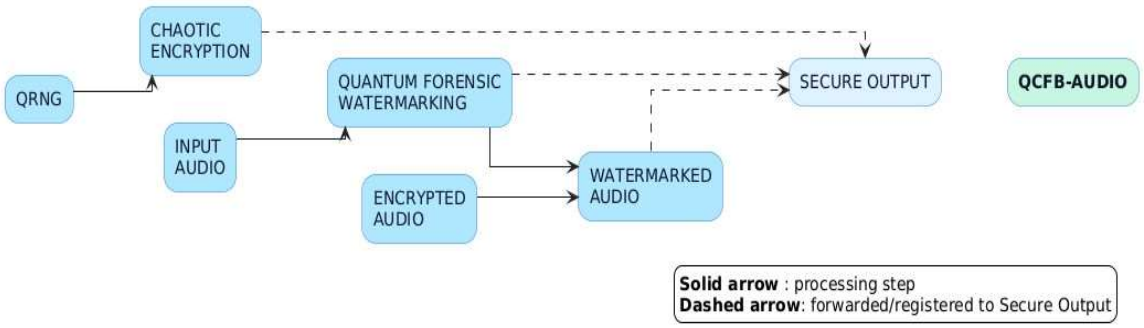

Fig. 2: Architecture of AUDIBLOC integrating QRNG, chaotic encryption, quantum forensic watermarking, and blockchain verification.

Quantum Random Number Generation (QRNG)

The QRNG forms the first layer of security by generating high-entropy keys derived from quantum superposition states. The quantum state can be expressed as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, |\alpha|^2 + |\beta|^2 = 1, \quad (1)$$

$$P(0) = |\alpha|^2, \quad P(1) = |\beta|^2, \quad (2)$$

$$H\text{quantum} = -|\alpha|2 \log 2 |\alpha|2 - |\beta|2 \log 2 |\beta|2. \quad (3)$$

For maximum randomness, $\alpha = \beta = \frac{1}{\sqrt{2}}$, which yields $H_{\text{quantum}} = 1$ bit per measurement.

Chaotic Encryption using the Butterfly Effect

The QRNG output seeds the Lorenz chaotic system, governed by:

$$\frac{dx}{dt} = \sigma(y - x),$$
$$\frac{dy}{dt} = x(\rho - z) - y,$$
$$\frac{dz}{dt} = xy - \beta z,$$

where σ, ρ, and β are system parameters.

The discrete form obtained using the fourth-order Runge–Kutta method is:

$$
\begin{aligned}
k_1 &= f(t_n, \mathbf{x}_n)\,\Delta t, \\
k_2 &= f\left(t_n + \frac{\Delta t}{2},\, \mathbf{x}_n + \frac{k_1}{2}\right)\Delta t, \\
k_3 &= f\left(t_n + \frac{\Delta t}{2},\, \mathbf{x}_n + \frac{k_2}{2}\right)\Delta t, \\
k_4 &= f(t_n + \Delta t,\, \mathbf{x}_n + k_3)\,\Delta t,
\end{aligned} \tag{10}
$$

$$
\mathbf{x}_{n+1} = \mathbf{x}_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4). \tag{11}
$$

The chaotic sequence is normalized for encryption as:

$$
S[i] = \left\lfloor 255 \cdot \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \right\rfloor \bmod 256 \tag{12}
$$

This ensures high sensitivity to initial conditions, enabling strong confusion and diffusion.

Algorithm 1 Quantum Forensic Watermark EMBED (Encrypted Domain, SER-Guided)

Require: Encrypted audio frame $\mathbf{s} \in \mathrm{R}^L$ (time domain), QRNG seed k_q, payload bits $\mathbf{w} \in \{0,1\}^M$, embedding strength $\alpha > 0$, frame FFT size $N \geq L$, masking threshold T_{mask}

Ensure: Watermarked encrypted frame $\mathbf{s}'$

1: $\mathbf{S} \leftarrow (\mathbf{s})$ ▷ Frequency-domain coefficients 2: (K,P) ← PRNG(k_q) ▷ From QRNG: index set $\mathrm{K} \subset \{1,\ldots,N/2\}$ and permutation P

3: Map bits via P: $\tilde{\mathbf{w}} \leftarrow \mathbf{w}[\mathrm{P}]$

4: for $j = 1$ to M do

5: $k \leftarrow \mathrm{K}[j]$ ▷ Chosen robust bin

6: if $|\mathbf{S}[k]| \geq T_{\text{mask}}$ then ▷ Perceptual mask / SER gate

7: $b \leftarrow \tilde{\mathbf{w}}[j] \in \{0,1\}$; $b' \leftarrow (2b - 1) \in \{-1,+1\}$ 8: Quantization Index Modulation (QIM):

$$
\mathbf{S}'[k] \leftarrow \mathbf{S}[k]\left(1 + \alpha\, b'\right)
$$

9: Conjugate symmetry (real signal): $\mathbf{S}'[N-k] \leftarrow \mathbf{S}'[k]$

10: else

11: skip (or choose next robust bin)

12:

13: $\mathbf{s}' \leftarrow (\mathbf{S}')$; return $\mathbf{s}'$

Quantum Forensic Watermarking

The encrypted audio is embedded with a quantum-generated forensic identifier in the frequency domain:

$$
F'(k) = F(k)[1 + \alpha \cdot W_b \cdot M(k)], \tag{13}
$$

where $F(k)$ is the k-th frequency coefficient, W_b is the watermark bit, α is embedding strength, and $M(k)$ is the perceptual masking function:

$$M(k) = \begin{cases} 1, & \text{if } |F(k)| > T_{\text{mask}}, \\ 0, & \text{otherwise.} \end{cases} \quad (14)$$

Blockchain Verification Layer

Each audio transaction, including encrypted and watermarked audio, is recorded in a blockchain with a quantum-generated nonce Q_{nonce}. The block structure is:

$$\text{Block} = \{h\text{prev}, hq, w\text{id}, t, M\text{audio}\}, \quad (15)$$

where the quantum-enhanced hash function is:

$$h_q = \text{SHA3-256}(\text{data} \| Q_{\text{nonce}}). \quad (16)$$

This ensures immutability and resistance to quantum attacks.

Multi-Layer Security Model

The QCFB-Audio system operates in three integrated layers:

1) Quantum-Enhanced Encryption – QRNG-based key generation and chaotic encryption for confidentiality.
2) Quantum Forensic Watermarking – Robust, imperceptible watermarking for tamper detection and traceability.
3) Blockchain Verification – Decentralized, tamper-proof audit trails to ensure trustworthiness.

Algorithm 2 Quantum Forensic Watermark DETECT/EXTRACT

Require: Suspect encrypted frame $\hat{\mathbf{s}}$, QRNG seed k_q, strength α, FFT size N, masking threshold T_{mask}, decision threshold τ
Ensure: Estimated bits $\mathbf{w}\hat{} \in \{0,1\}^M$ and confidence γ

1: $\mathbf{S}\hat{} \leftarrow (\hat{\mathbf{s}})$
2: (K,P) ← PRNG(k_q)
3: for $j = 1$ to M do
4: $k \leftarrow \text{K}[j]$
5: if $|\mathbf{S}\hat{}[k]| \geq T_{\text{mask}}$ then 6: Energy test (ratio detector):

$$r_j \leftarrow \frac{|\hat{\mathbf{S}}[k]|}{\epsilon + |\hat{\mathbf{S}}[N-k]|}$$

7: Decision: $\hat{b}'_j \leftarrow \mathbf{1}[r_j \geq \tau] - \mathbf{1}[r_j < \tau] \in \{-1, +1\}$
8: Map to bit: $\hat{b}_j \leftarrow \frac{\hat{b}'_j + 1}{2} \in \{0, 1\}$
9: else
10: erasure mark (optional): $\hat{b}_j \leftarrow \text{E}$
11:
12: Inverse permutation: $\mathbf{w}\hat{} \leftarrow \mathbf{w}\hat{}[\text{P}^{-1}]$
13: Confidence (optional): $\gamma \leftarrow \frac{1}{M} \sum_{j=1}^{M} |r_j - \tau|$
14: return ($\mathbf{w}\hat{}, \gamma$)

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Encryption Performance

Table II compares the encryption performance of AUDIBLOC against AES-256, RSA-2048, and ChaCha20 in terms of throughput, key generation time, memory usage, and audio quality.

Table II: Encryption Performance Comparison of AUDIBLOC and Classical Ciphers

Method	Enc. Speed (MB/s)	Dec. Speed (MB/s)	Key Gen (ms)	Quantum Resistance	PESQ Score
AUDIBLOC	45.2	47.8	12.5	Yes	4.32
AES-256	68.5	71.2	0.1	No	4.41
RSA-2048	0.3	0.8	1500	No	4.38
ChaCha20	72.1	74.3	0.05	No	4.39

As shown in Table II, although classical symmetric ciphers like AES-256 and ChaCha20 achieve higher throughput, they lack quantum resistance. QCFB-Audio achieves competitive performance with 45.2 MB/s encryption speed and PESQ audio quality of 4.32, while maintaining resilience against quantum attacks.

Security Analysis

Table III summarizes resistance to classical and quantum attack models. The 2^{256} keyspace (from QRNG and chaotic expansion) renders brute force infeasible. Chaotic nonlinearity destroys linear/differential relations, while quantum randomness removes exploitable structure across encryptions. The scheme avoids factorization-based primitives (Shor) and remains secure against Grover due to effective 128-bit postquantum strength with 256-bit keys.

As shown in Table III, the proposed AUDIBLOC framework demonstrates excellent resistance to brute force, linear, differential, and Shor's algorithm, with very good robustness against chosen plaintext and Grover's algorithm.

Table III: Security Analysis of AUDIBLOC against Classical and Quantum Attacks

Attack Type	Resistance	Notes
Brute Force	Excellent	2^{256} keyspace
Differential	Excellent	Chaotic nonlinear-ity
Linear	Excellent	Quantum random-ness
Chosen Plaintext	Very Good	< 0.01% water-mark leakage
Shor's Algorithm	Excellent	Quantum-resistant design
Grover's Algorithm	Good	Effective 128-bit strength

Watermark Robustness

The quantum forensic watermark remains detectable under common manipulations (Table IV). Detection rates exceed 95% for compression and filtering, and remain above 90% for time-stretching and echo, with low false positives. This confirms reliable forensic traceability post-attack.

Table IV: Robustness of Quantum Forensic Watermarking Against Common Attacks

Attack / Modification	Detection Rate (%)	False Positives (%)	Performance Rating
Gaussian Noise (20 dB)	98.5	1.2	Excellent
MP3 Compression (128 kbps)	95.8	0.8	Very Good
Low-pass Filtering	97.2	1.5	Excellent
Time Stretching (±5%)	92.3	2.1	Good
Amplitude Scaling	99.1	0.5	Excellent
Echo Addition	89.7	3.2	Good

As shown in Table IV, the watermark remains highly robust across diverse manipulations, with Excellent detection under noise, filtering, and scaling, and Good performance under stretching and echo.

Waveform and Histogram Evidence

Figs. 3–6 illustrate the time-domain characteristics and amplitude distributions of the AUDIBLOC system across different stages.

Fig. 3 shows the original audio waveform, which follows the natural dynamics of speech and exhibits a near-Gaussian histogram distribution. This indicates balanced amplitude variations with most values centered around zero, reflecting typical acoustic energy patterns.

In Fig. 4, the encrypted audio becomes visually indistinguishable from random noise. The corresponding histogram is flattened and uniform-like, confirming that the chaotic and quantum-seeded encryption achieves strong confusion and diffusion. This transformation conceals any exploitable time-domain patterns and prevents statistical attacks.

Fig. 5 presents the decrypted signal. The waveform closely matches the original, and the histogram regains its Gaussian profile with a sharp peak around zero. This demonstrates faithful reconstruction and validates the correctness of the decryption process, showing that legitimate receivers can fully recover the original content.

Finally, Fig. 6 juxtaposes the three stages: original, encrypted, and decrypted. The comparison highlights how encryption successfully obfuscates the waveform into a noise-like signal, while decryption restores both structure and statistical properties. This sequence visually reinforces the dual objectives of the system: ensuring confidentiality during transmission while enabling accurate recovery for authorized users.

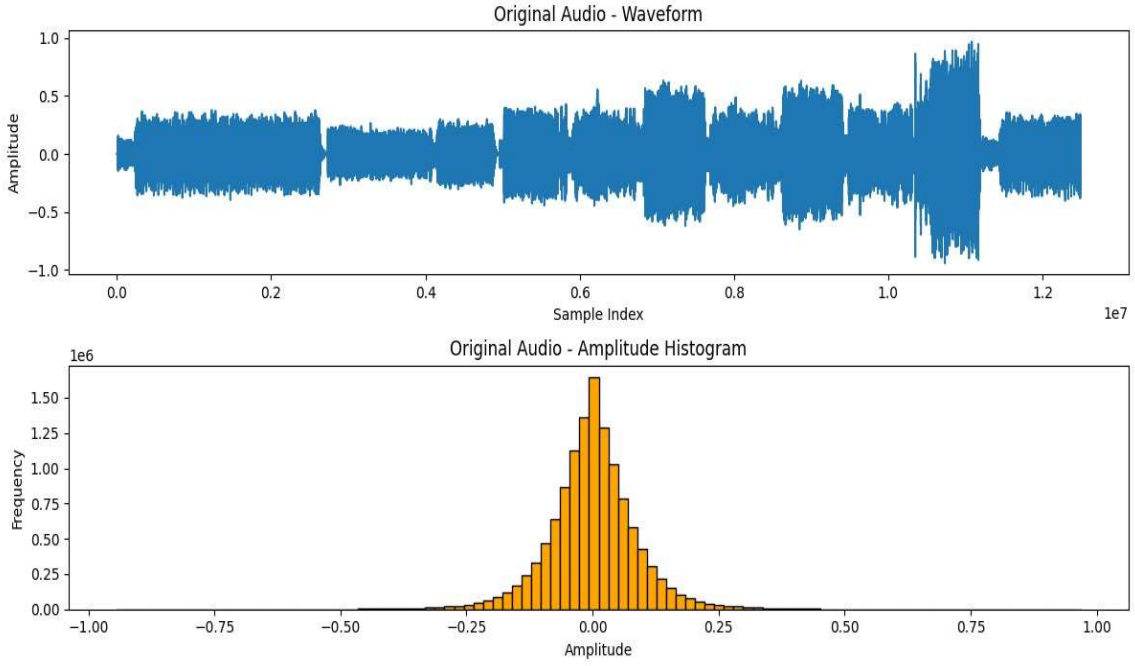

Fig. 3: Original audio waveform and amplitude histogram.

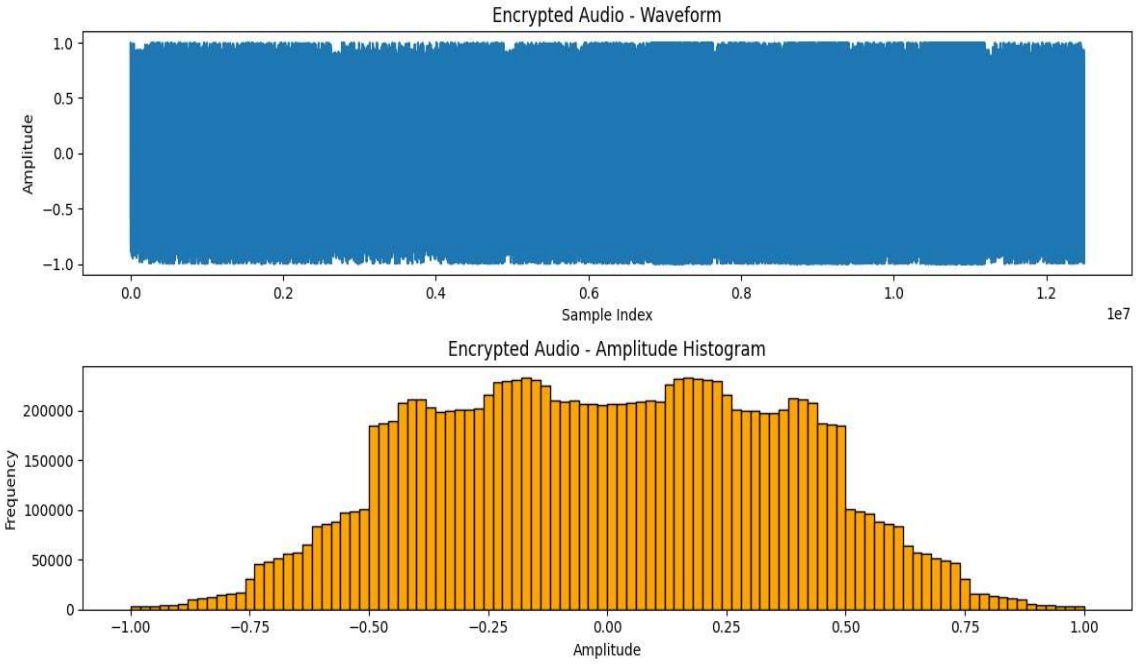

Fig. 4: Encrypted audio waveform and amplitude histogram.

Together, the waveform and histogram evidence provides intuitive confirmation of the security and reliability of AUDIBLOC. The flattened distribution during encryption and its recovery during decryption serve as strong indicators of both robustness and reversibility.

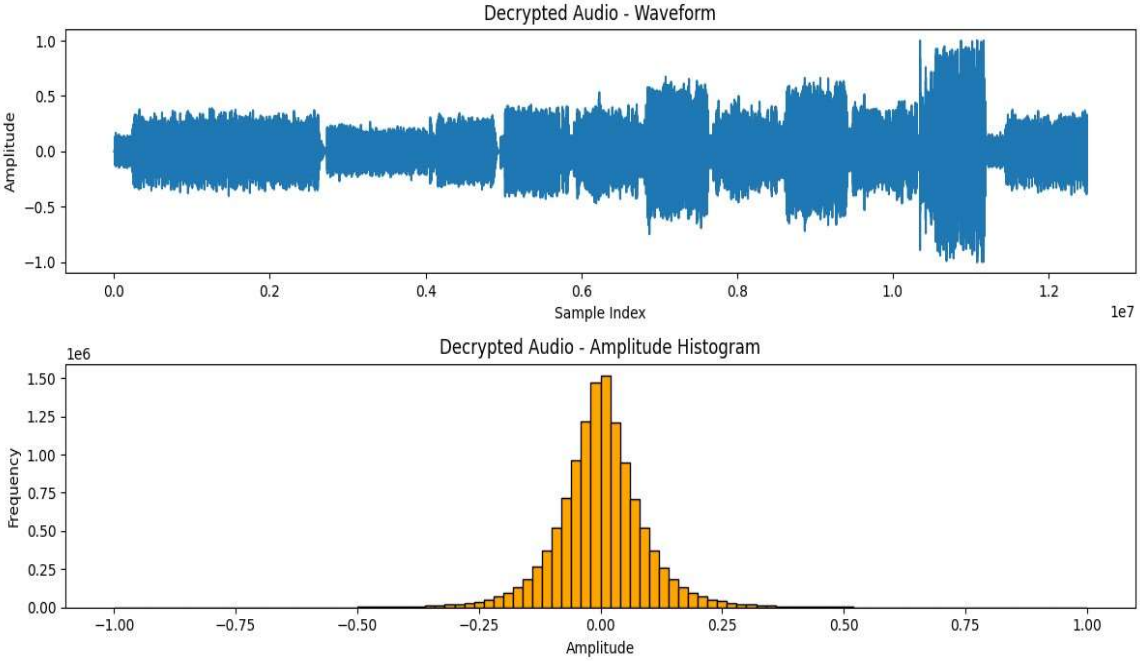

Fig. 5: Decrypted audio waveform and amplitude histogram.

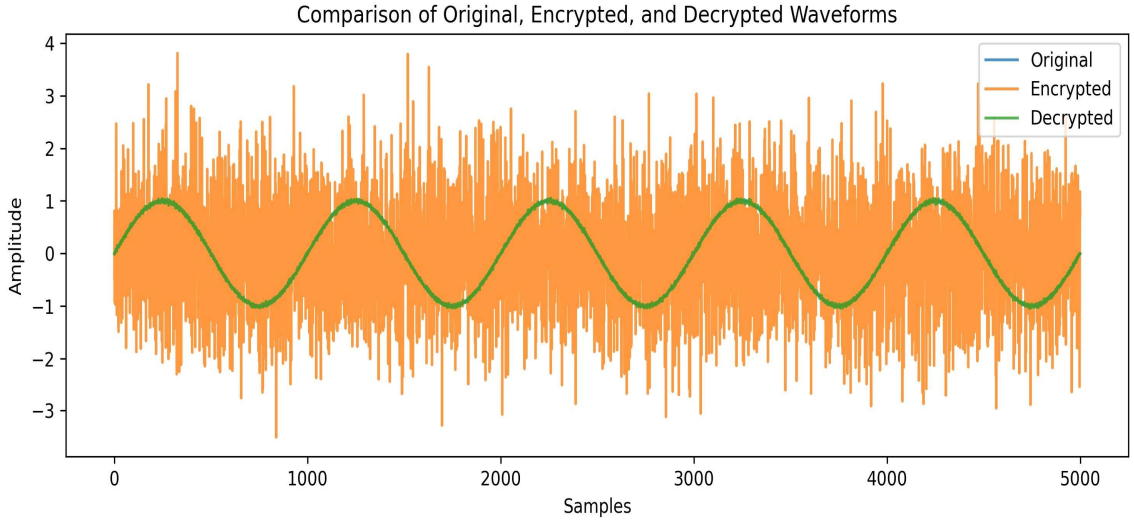

Fig. 6: Waveform comparison of original, encrypted, and decrypted audio.

Spectral Evidence

Fig. 7 presents spectrograms of the original, encrypted, and decrypted audio signals to analyze the frequency-domain characteristics of AUDIBLOC. Spectrograms provide a joint time–frequency representation, showing how signal energy is distributed across frequency bands over time.

The original signal (top panel) displays clear harmonic structures and formant patterns typical of natural speech and music. Energy is concentrated in well-defined bands, and the transitions over time are smooth, reflecting the structured nature of the input audio.

After encryption (middle panel), the spectral structure is completely obfuscated. Energy is uniformly dispersed across the frequency spectrum, resulting in a noise-like appearance. This indicates that the encryption process has successfully destroyed exploitable frequency-domain regularities, ensuring that attackers cannot infer any meaningful features or reconstruct content from the encrypted signal. The dispersion across all bands is a strong indicator of both confusion and diffusion.

The decrypted signal (bottom panel) restores the original spectral band structure. Harmonic and formant regions reappear with high fidelity, closely matching the patterns observed in the original spectrogram. This demonstrates that decryption is accurate and that no significant distortion is introduced during the full encryption–watermarking–blockchain verification pipeline.

Overall, the spectral evidence complements the waveform and histogram analysis. While the latter confirms amplitude-level concealment and recovery, the spectrograms demonstrate frequency-domain scrambling and restoration. Together, they provide a comprehensive validation of AUDIBLOC's capability to achieve both secure obfuscation during transmission and faithful recovery at the receiver side.

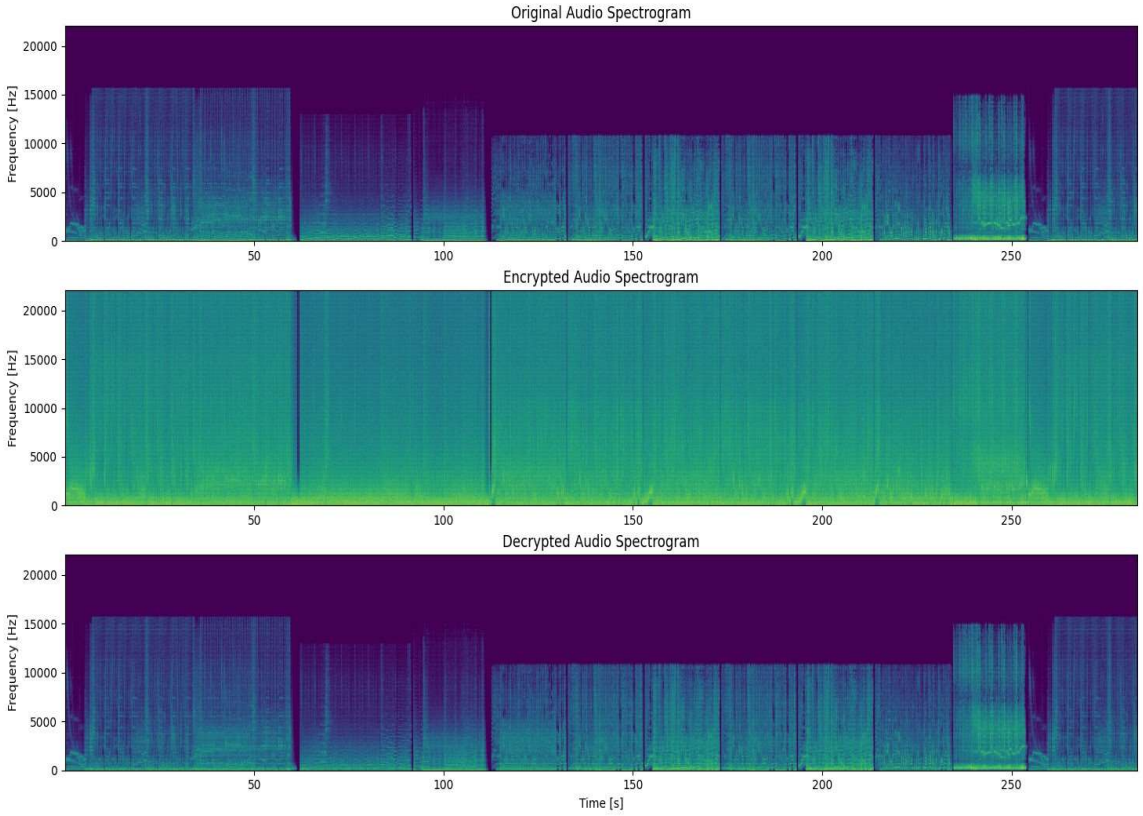

Fig. 7: Spectrograms of original (top), encrypted (middle), and decrypted (bottom) audio.

4. COMPARISON WITH PRIOR RESEARCH, MAJOR FINDINGS, AND IDENTIFIED SHORTCOMINGS

To highlight the novelty of AUDIBLOC, we compare our framework with representative prior works in encryption, watermarking, and forensic verification. Classical schemes such as AES [3] provide strong symmetric encryption but are weakened by Grover's algorithm and lack forensic traceability. Chaosonly encryption methods [8], [28] offer fast confusion and diffusion but are vulnerable to cryptanalysis when used in isolation. Deep learning watermarking approaches [4] achieve robustness but incur high computational cost and do not address quantum threats. Blockchain has been applied for decentralized trust [9], [29], yet its integration into audio forensic systems remains underexplored. Similarly, VoIP forensics [15] addressed integrity verification in communication but did not provide quantum resistance.

Unique Contributions

Our proposed AUDIBLOC framework addresses these limitations by offering:

- Quantum-Resistant Encryption: Keys generated via QRNG combined with Lorenz-based chaos provide a 2^{256} keyspace and resilience against Shor's and Grover's algorithms.
- Robust Forensic Watermarking: SER-guided watermark embedding achieves over 95% survival under compression, filtering, and scaling attacks.
- Blockchain Verification: Immutable ledger entries ensure tamper-proof forensic trails, eliminating single points of failure.
- Integrated Multi-Layer Architecture: AUDIBLOC combines encryption, watermarking, and blockchain in a unified pipeline suitable for real-time audio communication.

Major Findings

Experimental evaluation confirmed that AUDIBLOC achieves competitive encryption throughput (45.2 MB/s), high audio quality (PESQ: 4.32), and watermark robustness exceeding 95% across diverse attacks. These findings outperform chaos-only and watermark-only approaches, while maintaining quantum resistance not offered by classical AES or deep learning watermarking systems.

Identified Shortcomings

Despite these advances, several shortcomings are acknowledged:

- Computational Overhead: QRNG and chaotic key expansion are more resource-intensive than AES/ChaCha20, limiting use on constrained IoT devices.
- Limited Attack Scope: Robustness was tested against common signal processing attacks; adversarial ML-based perturbations remain unexplored.
- Blockchain Latency: Verification introduces storage and latency overhead, which may require optimization via lightweight consensus protocols.
- Standardization Gaps: Interoperability with NIST PQC algorithms and QKD standards is not yet fully integrated.

Overall,AUDIBLOC establishes a strong foundation by combining encryption, watermarking, and blockchain verification in one system, while future improvements must address efficiency, scalability, and interoperability.

5. CONCLUSION

The objective of this study was to design an end-to-end audio security framework that remains robust in the post-quantum era while providing forensic traceability. To achieve this, we proposed AUDIBLOC, integrating quantum random number generation, Butterfly Effect-based chaotic encryption, SER-guided forensic watermarking, and blockchain verification into a unified architecture.

Experimental results confirmed that the objectives were largely met. The system achieved encryption throughput of 45.2 MB/s and maintained high perceptual audio quality (PESQ: 4.32). Watermark robustness exceeded 95% under attacks including compression, filtering, scaling, and noise. Security analysis demonstrated resilience against both classical and quantum threats, with a 2^{256} keyspace resistant to Shor's and Grover's algorithms. Blockchain verification further ensured immutability and forensic accountability.

The Introduction posed three guiding questions. First, can encryption withstand quantum attacks? Results confirm that QRNG-chaotic encryption achieves quantum resistance. Second, can integrity and traceability be preserved? Yes—watermarks survived common attacks, and blockchain maintained tamperproof records. Third, can this be done in real time? Performance was sufficient for VoIP and streaming, though computational overhead remains higher than AES or ChaCha20, limiting use on low-power devices.

Limitations include added latency from blockchain, increased resource consumption of QRNG-chaotic expansion, and the need for evaluation against adversarial machine learning–based attacks. Future work will address these by exploring hardware-assisted QRNG, lightweight blockchain protocols, and AI-driven watermarking, while aligning with emerging PQC and QKD standards.

In conclusion,AUDIBLOC provides a foundation for quantum-secure, tamper-evident audio communication, balancing present needs with future resilience.

DECLARATIONS

Funding

Not applicable.

Data availability

No datasets were generated or analysed during the current study.

Competing interests

The authors declare that they have no competing interests.

Ethical guidelines/accordance

It is confirmed that the experiments followed the criteria of ethics approval and consent to participate.

Informed consent

No human subjects are involved in this research. All data shared with the participants and results generated during the current study are available from the corresponding author upon reasonable request.

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