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SECURING DATA EXCHANGE CHANNELS BETWEEN PYTHON APPLICATIONS USING CRYPTOGRAPHIC LIBRARIES

Abstract. Topicality. The increasing reliance on distributed applications highlights the urgent need for secure data exchange channels between software components. Without appropriate protection, communication is exposed to threats such as eavesdropping, spoofing, tampering, and replay attacks. **The subject of study** in the article is the use of Python's cryptographic libraries (cryptography, PyNaCl) for constructing lightweight yet robust security layers on top of existing communication mechanisms. **The purpose of the** article is to present a practical and reproducible method for securing message flows by combining symmetric encryption (AES-GCM), ephemeral key exchange (X25519), key derivation (HKDF with SHA-256), and digital signatures (Ed25519). **The following results** were obtained. The proposed model integrates authenticated encryption with associated data (AEAD) and session counters to mitigate replay risks, while maintaining compatibility with various transports such as HTTP, gRPC, and MQTT. The study provides minimal, clear code examples and performance measurements showing that the system achieves encryption and decryption in less than one millisecond for typical payloads, with key exchange and signature operations adding only a few milliseconds. These results demonstrate that strong cryptographic protection can be achieved without significant performance penalties. **Conclusion.** The findings confirm the suitability of the proposed scheme for real-time distributed systems, microservices, and IoT environments. Future improvements may include post-quantum cryptography integration and automated key management.

Keywords: Python applications; secure communication; AES-GCM; X25519; Ed25519; HKDF; replay protection.

Introduction

Problem Relevance. Distributed applications form the foundation of today's information systems. They constantly exchange data through network protocols, APIs, or message queues. These data exchanges may include service events, user identifiers, access tokens, financial transactions, or files with confidential information.

If such data are transmitted without protection, they become vulnerable to a range of attacks, including:

- Eavesdropping – an attacker intercepts and reads the data in transit.
- Spoofing – impersonation of a sender or receiver.
- Tampering – unauthorized modification of messages.
- Replay attacks – resending previously captured messages to deceive the system.

Python is one of the most widely used programming languages globally. It powers web servers, microservices, automation systems, and IoT solutions. All of these systems rely heavily on secure data exchange, making this problem highly relevant for both researchers and practitioners.

Fortunately, Python provides mature libraries for cryptography, such as cryptography, PyNaCl, and the standard hashlib. They allow developers to design hybrid protection schemes that combine:

- symmetric encryption (e.g., AES-GCM, ChaCha20-Poly1305) for fast traffic protection;
- asymmetric key exchange (e.g., X25519, RSA) for secure key distribution;
- digital signatures (e.g., Ed25519, RSA-PSS) for authentication;
- hashing for integrity verification.

Literature Review. Research and standards emphasize that no single cryptographic primitive can ensure full security. Instead, robust systems combine multiple primitives.

The best practices are:

- AES-GCM or ChaCha20-Poly1305 – authenticated encryption with associated data (AEAD) for data confidentiality and authenticity.
- X25519 or RSA-OAEP – secure key exchange.
- Ed25519 or RSA-PSS – digital signatures to verify authenticity.
- HKDF (SHA-256) – for key derivation.
- Key lifecycle management – including rotation, secure storage, and audit policies.

In Python, these cryptographic patterns are directly available through open-source libraries such as cryptography and PyNaCl.

Purpose and Research Objectives. Purpose: to demonstrate a practical method for building a secure communication channel between Python components without complex mathematical formulas, using minimal, simple code examples.

Objectives:

1. Select modern cryptographic primitives that comply with security standards.
2. Demonstrate a simple key exchange mechanism.

Implement message encryption and decryption.

3. Add digital signatures and verification for service data.
4. Introduce counters and protocol versions to mitigate replay attacks.
5. Evaluate performance and propose practical recommendations for key rotations [1, 2].

1. Implementing Secure Data Transmission Between Python Applications

Symmetric encryption is the foundation of secure communication. It uses the same key for encryption and decryption and is known for its speed and efficiency, making it suitable for real-time systems.

AES in Galois/Counter Mode (AES-GCM) is widely regarded as the most practical choice, because it provides both confidentiality and integrity.

```
from cryptography.hazmat.primitives.ciphers.aead import AESGCM
import os

key = AESGCM.generate_key(bit_length=256)
aes = AESGCM(key)
nonce = os.urandom(12)
aad = b"proto=1|sid=abc|seq=1"

ciphertext = aes.encrypt(nonce, b"secret data", aad)
plaintext = aes.decrypt(nonce, ciphertext, aad)
```

Fig. 1. Secure data transfer between Python programs using symmetric encryption

Key rules:

- Never reuse the same nonce with the same key.
- Place metadata (e.g., protocol version, session ID, message sequence number) in AAD for integrity protection.
- Handle keys securely: they should not be hardcoded or logged.

This simple example shows how developers can encrypt and authenticate messages in just a few lines of code.

The significance of this implementation lies in its simplicity: a complete cycle of encryption and decryption can be expressed in fewer than ten lines of Python code, yet the underlying cryptographic protection is on par with industry standards used in TLS and VPNs. This makes AES-GCM particularly attractive for developers who need to integrate security into their systems without building a complex infrastructure from scratch.

AES-GCM works by combining counter mode encryption with the Galois Message Authentication Code (GMAC). Counter mode provides confidentiality by transforming AES into a stream cipher, while GMAC ensures message integrity by producing an authentication tag. The result is an Authenticated Encryption with Associated Data (AEAD) scheme, which simultaneously solves two critical problems: keeping the data secret and guaranteeing that it has not been tampered with. Unlike traditional approaches that used AES in CBC mode combined with a separate HMAC, AES-GCM integrates both tasks into a single efficient operation [4,5].

Another powerful concept in this scheme is the inclusion of Additional Authenticated Data (AAD). AAD allows applications to bind non-secret information—such as protocol versions, session identifiers, or sequence numbers—directly into the authentication process. Although this metadata is not encrypted, it becomes cryptographically tied to the message. If an attacker attempts to alter or remove this information, the decryption will fail. This ensures not only confidentiality but also structural integrity of the communication protocol itself.

Practical Considerations. In practice, the choice of nonce generation and key management is just as important as the encryption algorithm. Developers must ensure that every nonce used with a given key is unique; otherwise, the security guarantees of AES-GCM collapse. A common strategy is to derive nonces from sequence numbers or counters, guaranteeing uniqueness even under high loads. Key management should be automated wherever possible—manual handling or hardcoding keys into source code is one of the most common security mistakes in real-world deployments.

Furthermore, AES-GCM benefits significantly from hardware acceleration. Many modern processors include dedicated AES instructions, which allow encryption and decryption to be executed at near memory-copy speeds. This means that the cryptographic overhead for protecting each message is often negligible compared to the cost of transmitting the data over a network. In distributed systems with thousands of transactions per second, this property ensures that strong encryption can be deployed universally without sacrificing performance.

Broader Implications. From a system design perspective, the ability to implement secure communication with such minimal code lowers the barrier to adopting best practices. Even small development teams or projects with limited security expertise can add strong protection to their applications. In distributed environments where services frequently exchange sensitive tokens, credentials, or user data, this level of accessibility is crucial for preventing data breaches.

In summary, AES-GCM represents the cornerstone of secure data transmission in Python applications. Its combination of confidentiality, integrity, and efficiency makes it suitable not only for high-performance microservices but also for IoT devices and mobile systems. The Python ecosystem provides a mature, stable interface to this cryptographic primitive, allowing developers to implement strong, production-grade security in an accessible and reproducible manner.

2. Choosing a Cryptographic Architecture for Python Applications

While symmetric encryption is extremely efficient and well-suited for protecting large amounts of data, it does not on its own address the fundamental challenge of securely distributing encryption keys between communicating parties. If both ends of a communication channel do not already share a common secret, symmetric algorithms alone cannot establish trust or guarantee confidentiality at the moment of initial contact. This limitation makes it necessary to introduce additional mechanisms that can provide secure key exchange and authentication before encrypted communication can begin.

Hybrid cryptographic architectures were developed precisely to overcome this gap. By combining the efficiency of symmetric encryption with the robustness of asymmetric cryptography, they enable systems to establish secure communication channels even over untrusted networks. In practice, the hybrid model begins with an asymmetric key exchange mechanism that allows

two parties to agree on a shared secret without directly transmitting it. Once the secret is established, it is transformed into a session key through a key derivation function, and from that moment on, all data transmission can rely on fast symmetric encryption algorithms.

In the context of Python applications, the proposed architecture relies on a set of modern primitives that have become industry standards. For key exchange, the use of ephemeral X25519 provides an implementation of the Diffie-Hellman protocol that is both efficient and secure, while also enabling forward secrecy. This means that session keys are generated fresh for each session and are never reused, ensuring that even if a long-term private key is compromised in the future, previously exchanged data remains secure. Once the shared secret has been generated, it is processed through the HKDF construction with SHA-256, which guarantees that the derived keys have strong cryptographic properties and cannot be predicted from the original secret.

To protect the initial handshake against impersonation and man-in-the-middle attacks, digital signatures are integrated into the scheme. Ed25519 is employed for this purpose, offering high security with excellent performance. Each side can sign its handshake messages and verify those of its peer, ensuring that only legitimate parties can participate in the exchange. Furthermore, the architecture incorporates additional authenticated data, which includes information such as protocol version, session identifiers, and sequence numbers. This extra layer of authenticated metadata prevents protocol downgrades and replay attacks, giving the system resilience against common real-world threats.

The strength of this architecture lies in its balance between efficiency and security. Symmetric encryption ensures that the actual transmission of data is fast and reliable, while the asymmetric components and integrity checks guarantee that only the right parties can communicate and that every session is cryptographically unique. For Python developers, the availability of mature libraries such as cryptography and PyNaCl means that implementing this design does not require deep cryptographic expertise. Instead, developers can focus on the correct combination of primitives, confident that the underlying implementations are secure and optimized.

Ultimately, the adoption of a hybrid cryptographic architecture in Python applications ensures authenticity, forward secrecy, and robustness against replay or downgrade attacks. It transforms communication between distributed components into a secure and verifiable process that is both practical and resilient to adversarial conditions.

3. Modeling the Secure Communication Process

The secure channel establishment follows these steps:

1. Both parties possess long-term Ed25519 keys. Public keys are exchanged out-of-band beforehand.
2. At the start of a session, each side generates an ephemeral X25519 key pair.
3. Party A sends to Party B: *eph_pub_A, session_id, proto_version*, and a digital signature of these values.
4. Party B verifies the signature, then responds with its own *eph_pub_B* and signature.
5. Both sides compute the shared secret via X25519 and derive a session AES-GCM key using HKDF.
6. All subsequent messages are encrypted using AES-GCM with metadata included in AAD.

```
from nacl import public, signing

eph_sk = public.PrivateKey.generate()
eph_pk = eph_sk.public_key

sign_sk = signing.SigningKey.generate()
sign_pk = sign_sk.verify_key

payload = b"session_id=s1|proto=1|eph_pub=" + bytes(eph_pk)
signature = sign_sk.sign(payload).signature
sign_pk.verify(payload, signature)  # verification
```

Fig. 2. The result of modeling the secure communication process

This handshake ensures mutual authentication and forward secrecy.

After the initial handshake phase is completed, the secure communication process transitions into the data exchange stage, where all subsequent messages are protected with the derived AES-GCM session key. At this point, the system has achieved two critical guarantees: first, that both participants are indeed who they claim to be, and second, that the confidentiality of past and future sessions is preserved even in the event of long-term key compromise. This combination of mutual authentication and forward secrecy elevates the protocol beyond basic transport security, creating a robust foundation for application-level protection.

An important aspect of the model is the handling of metadata. Each encrypted message includes associated data that is bound to the ciphertext through the AEAD mechanism. This metadata typically contains the protocol version, session identifier, and a monotonically increasing sequence number. Binding these fields to the cryptographic operation ensures that they cannot be altered or replayed by an attacker. For example, if an adversary were to intercept and resend an earlier packet, the receiving application would immediately detect the duplication because the sequence number would not align with the expected order. In this way, replay attacks are neutralized by the inherent design of the system.

Equally critical is the resilience of the protocol to downgrade attacks. By explicitly authenticating the protocol version in every message, the system prevents adversaries from coercing participants into using weaker cryptographic algorithms. If a malicious intermediary attempted to strip version information or replace it with an outdated identifier, the authentication tag produced by AES-GCM would fail verification, immediately exposing the manipulation attempt. This provides strong assurance that the integrity of the negotiation phase is preserved throughout the lifetime of the communication

session.

The practical modeling of this process also takes into account operational requirements such as key rotation and session expiration. Since ephemeral keys are generated for every session, the natural outcome is a system that periodically refreshes its security state. However, for long-running services, it is advisable to implement explicit rotation policies, for instance, by renegotiating the handshake after a fixed time interval or a specified number of messages. This strategy minimizes the impact of potential key leakage and ensures that any compromised session secrets have only a limited window of usefulness to an attacker.

Another valuable property of the model is its transport independence. Because the handshake and encryption mechanisms operate at the application layer, they can be applied consistently across a wide variety of channels. Whether messages are transmitted over HTTP, gRPC, MQTT, or even custom file-based pipelines, the cryptographic guarantees remain identical. This universality simplifies the architecture of distributed systems by decoupling security from the underlying transport, making the approach adaptable to heterogeneous infrastructures.

Finally, the strength of the modeled process lies in its clarity and reproducibility. The steps are transparent, the cryptographic primitives are well-studied, and the implementation can be achieved with only a few lines of Python code using trusted libraries. This lowers the barrier to adoption, enabling even non-specialist developers to construct systems with robust end-to-end security. By capturing the handshake, key exchange, session derivation, and message authentication in a single coherent model, the protocol offers both theoretical soundness and practical applicability for real-world distributed environments [3].

4. Measuring the Average Time for Secure Message Transmission

Performance evaluation of cryptographic mechanisms is a crucial step in building secure systems. Even if algorithms provide a high level of theoretical security, excessive computational overhead can lead to delays that make the system unsuitable for real-time usage. Therefore, it is necessary to analyze the average execution time of encryption, decryption, key exchange, and signature operations under typical conditions.

The main goal of the measurements was to evaluate:

1. The speed of symmetric encryption (AES-GCM) for messages of different sizes.
2. The cost of asymmetric key exchange (X25519).
3. The performance of signature generation and verification (Ed25519).
4. The overall impact of these operations on message exchange between Python applications.

The experiment was conducted on a mid-range laptop with an Intel i5 processor, running Python 3.11. To reduce measurement error, hundreds of iterations were executed for each operation, and the arithmetic mean was calculated.

Results:

1. AES-GCM: less than 1 ms per 4 KB message.
2. X25519: approximately 3–5 ms to establish a shared secret.
3. Ed25519: signature or verification takes about 0.3 ms.

For comparison, *ChaCha20-Poly1305*, which is often preferred in mobile and embedded systems, produced similar results, but demonstrated more consistent performance on low-power devices.

```
import os, time
from statistics import mean
from cryptography.hazmat.primitives.ciphers.aead import AESGCM

key = AESGCM.generate_key(256)
aes = AESGCM(key)
msg = os.urandom(4096)   # 4 KB message
aad = b"proto=1|sid=s|seq=1"

enc, dec = [], []
for _ in range(300):
    nonce = os.urandom(12)
    t0 = time.perf_counter()
    ct = aes.encrypt(nonce, msg, aad)
    t1 = time.perf_counter()
    _ = aes.decrypt(nonce, ct, aad)
    t2 = time.perf_counter()
    enc.append(t1 - t0)
    dec.append(t2 - t1)

print("AES enc avg, ms:", mean(enc)*1e3)
print("AES dec avg, ms:", mean(dec)*1e3)
```

Fig. 3. The result of measuring the average time for secure message transmission

The performance evaluation confirmed that modern cryptographic primitives used in Python applications are highly efficient and suitable for real-world systems. The measurements showed that AES-GCM encryption and decryption of a 4 KB message consistently required less than a millisecond. This result highlights the efficiency of symmetric encryption: its computational overhead is practically negligible compared to the network latency usually encountered in distributed applications. In other words, the time spent on encrypting or decrypting data is overshadowed by the delays introduced by transport protocols or physical network conditions, making AES-GCM an excellent default choice for high-throughput environments.

The asymmetric key exchange mechanism, based on X25519, demonstrated an average cost of approximately three to five milliseconds for establishing a shared secret. Although this operation is slower than symmetric encryption, its impact is limited because it occurs only once per session, during the initial handshake or at planned rekeying intervals. In long-lived sessions, the relative cost of X25519 quickly diminishes, since the initial few milliseconds are amortized across potentially thousands of subsequent encrypted messages. This characteristic confirms that ephemeral key exchanges can be integrated

into real-time communication systems without creating a performance bottleneck.

Digital signature operations with Ed25519 proved to be even more efficient, with both signing and verification completing in roughly 0.3 milliseconds. This level of performance makes it realistic to embed signatures into the handshake process or even apply them selectively to critical metadata without significantly affecting throughput. Signatures add authenticity guarantees that symmetric encryption alone cannot provide, ensuring that even if a communication channel is compromised, messages cannot be forged without detection.

When compared to ChaCha20-Poly1305, a cipher often deployed in mobile and embedded environments, AES-GCM showed nearly identical results on general-purpose hardware. However, the analysis revealed that ChaCha20-Poly1305 performs more consistently on low-power devices that lack AES hardware acceleration. This finding suggests that the choice between AES-GCM and ChaCha20-Poly1305 should be guided by the target platform. Systems running on modern processors with built-in AES instructions will benefit most from AES-GCM, while IoT devices and battery-powered hardware may gain advantages from ChaCha20-Poly1305's predictable performance profile.

Overall, the experimental results demonstrate that the main source of latency in secure communication does not stem from message encryption itself but from the establishment of new sessions. Once the handshake has been completed, the efficiency of symmetric encryption ensures that secure communication can proceed with minimal delay. These insights confirm that hybrid cryptographic schemes combining X25519, Ed25519, and AES-GCM (or ChaCha20-Poly1305) provide strong security without imposing unacceptable computational costs.

These findings also carry direct implications for system design. In microservices and distributed systems, where large numbers of requests are processed per second, AES-GCM can be deployed with confidence, knowing that it will not become a performance bottleneck. In IoT scenarios, ChaCha20-Poly1305 may be preferable, as it delivers more predictable behavior on resource-constrained CPUs. Finally, the introduction of structured key rotation strategies allows developers to balance strong security with sustained performance, ensuring that communication channels remain protected without introducing excessive overhead [6].

5. Practical Optimization of Cryptographic Parameters

Optimizing cryptographic parameters is about finding the right balance between performance and security.

Best practices include:

1. Key rotation – regenerate session keys after a fixed number of messages or time interval.
2. Sequence numbers – each message must have a strictly increasing counter to prevent replays.
3. Two active keys during rotation – so delayed messages are not lost.
4. Protocol versioning in AAD – prevents downgrade attacks.

The challenge of applying cryptography in distributed applications is not limited to choosing secure primitives; it also involves tuning parameters and operational rules to ensure that the system remains both secure and efficient. Practical optimization therefore requires careful planning of key rotation, sequence tracking, version control, and error tolerance during key transitions.

One of the fundamental practices is the periodic rotation of session keys. Even though AES-GCM provides robust protection, reusing the same session key for an indefinite period introduces risks. To mitigate these risks, session keys should be regenerated either after a predefined number of encrypted messages or after a specific time interval. This practice reduces the amount of data encrypted with a single key, limiting the potential damage if a session secret were ever exposed.

```python
class Session:
    def __init__(self, key):
        self.key, self.seq = key, 0

    def pack(self, data):
        from cryptography.hazmat.primitives.ciphers.aead import AESGCM
        aes = AESGCM(self.key)
        self.seq += 1
        aad = f"proto=1|sid=s|seq={self.seq}".encode()
        nonce = os.urandom(12)
        ct = aes.encrypt(nonce, data, aad)
        return {"nonce": nonce, "aad": aad, "ct": ct, "seq": self.seq}

    def unpack(self, pkt):
        from cryptography.hazmat.primitives.ciphers.aead import AESGCM
        aes = AESGCM(self.key)
        return aes.decrypt(pkt["nonce"], pkt["ct"], pkt["aad"])
```

Fig. 4. The result of practical optimization of cryptographic parameters

A second optimization involves strict enforcement of sequence numbers. Each message should carry a monotonically increasing counter, which the receiving side verifies against its expected state. This mechanism not only ensures that messages are processed in the correct order but also blocks replay attempts, where an adversary resends valid packets in an effort to confuse or disrupt the system. Sequence enforcement thus strengthens both security and reliability of the communication process.

To prevent message loss during rekeying, the model supports the temporary coexistence of two active keys: the new session key and the immediately preceding one. This overlap guarantees that any delayed or out-of-order messages encrypted under the previous key can still be decrypted correctly. Once the transition period has passed, the old key is retired, maintaining a balance between continuity of service and strong security guarantees.

Finally, protocol versioning embedded within the additional authenticated data (AAD) ensures that downgrade attacks are not possible. By cryptographically binding version information into every encrypted

message, the system guarantees that both sides are operating under the same cryptographic assumptions. Any attempt by an attacker to substitute an older, weaker protocol version would immediately cause verification failures, protecting the integrity of the system.

Together, these optimizations illustrate that secure communication is not solely a matter of algorithm selection but also of protocol design and operational discipline. By integrating key rotation policies, sequence validation, dual-key rekeying, and strict versioning, developers can construct communication systems that are not only cryptographically strong but also resilient in the face of practical deployment challenges.

Such a design not only protects against replays but also enforces protocol discipline.

6. Discussion of Results

The proposed cryptographic scheme demonstrates several important advantages that make it highly practical for modern distributed applications. One of the most notable strengths lies in its efficiency. The use of AES-GCM for symmetric encryption ensures that messages can be encrypted and decrypted in a fraction of a millisecond, even for payloads of several kilobytes. This level of performance is critical in environments where large volumes of data must be exchanged continuously, such as microservice-based architectures, IoT ecosystems, or real-time monitoring systems. The efficiency of AES-GCM also means that the security layer introduces no noticeable latency, making it compatible with interactive applications that demand quick response times.

Another significant aspect is the guarantee of forward secrecy achieved through ephemeral X25519 key pairs. By generating new session keys for each communication session, the system ensures that even if a long-term private key were compromised, past communications would remain secure. This property is particularly relevant in adversarial environments where persistent attackers may collect encrypted traffic for later decryption attempts. With forward secrecy in place, such efforts become useless, which significantly strengthens the resilience of the system.

Ease of integration is also worth emphasizing. Python provides accessible, well-documented libraries that allow developers to implement cryptographic mechanisms with only a few lines of code. This lowers the barrier for teams that may not have deep expertise in cryptography, enabling them to adopt strong security practices without the risk of introducing serious implementation errors. Additionally, because the proposed scheme is transport-agnostic, it is not tied to a specific communication channel. It can be applied equally well over HTTP, gRPC, MQTT, message queues, or even file-based communication. This flexibility means that the same cryptographic design can be reused across different layers of the system, simplifying security management.

Despite these advantages, certain limitations must be acknowledged. The approach still requires an initial trusted channel for the exchange of long-term public keys. Without such a mechanism, the system remains vulnerable to impersonation during the first contact. Moreover, strict adherence to key rotation policies is essential. While the cryptographic primitives themselves are secure, failure to rotate keys properly or to maintain counters for replay protection could create exploitable weaknesses. Finally, in a real production environment, it remains advisable to use TLS as a baseline transport-level protection. TLS provides compatibility with infrastructure components such as load balancers and reverse proxies, while the proposed lightweight scheme can serve as an additional end-to-end layer when application-level metadata protection is required.

The comparison with existing approaches highlights the conditions under which this solution is most appropriate. If a system only requires basic confidentiality during data transfer, a standard TLS channel is often sufficient and easier to maintain. However, in cases where end-to-end integrity and control over metadata are critical, or where replay protection must be enforced independently of the transport, the described cryptographic overlay becomes a more suitable option. It allows developers to embed security guarantees directly at the application layer, extending protection beyond the limits of transport-level encryption.

Beyond these observations, it is important to emphasize that the practical value of the proposed scheme lies not only in the efficiency of the chosen algorithms but also in their composability. The combination of AES-GCM, X25519, and Ed25519 produces a layered defense model in which different cryptographic primitives reinforce each other. AES-GCM ensures the confidentiality and integrity of the actual data payload, while X25519 guarantees that each session starts with a fresh and unique secret, and Ed25519 provides a verifiable identity to prevent impersonation. This interdependence creates a resilient structure that is far stronger than any single primitive used in isolation.

From an operational perspective, the scheme also facilitates a modular approach to system design. Since it operates entirely at the application layer, it can be embedded directly into message serialization frameworks, middleware, or RPC protocols without requiring changes at the network layer. This is particularly valuable in heterogeneous environments where multiple transports may coexist. Developers can secure HTTP APIs, gRPC calls, message queues, or even peer-to-peer file exchanges using the same cryptographic overlay, ensuring uniform protection across the entire system.

Another key implication is the ease of verification and audit. Because the protocol defines explicit roles for each cryptographic primitive and enforces structured metadata within the AAD field, it becomes straightforward to log and monitor cryptographic events. Security teams can track handshake initiations, key rotations, and signature verifications as auditable events. This not only supports compliance with data protection regulations but also simplifies incident response by providing cryptographically verifiable evidence of communication flows.

It is also worth noting that the scheme aligns with

emerging trends in security architecture, such as zero-trust networking and end-to-end encryption in distributed microservices. In a zero-trust model, no network path is assumed to be secure by default. Embedding cryptography at the application layer ensures that even if the transport layer is intercepted, or if an attacker gains partial access to the infrastructure, the confidentiality and integrity of the data remain intact. Similarly, in microservices, where messages often traverse multiple intermediaries, end-to-end protection ensures that only the originating and receiving services have access to plaintext data, reducing the attack surface.

Finally, while TLS will likely remain the backbone of secure transport for the foreseeable future, this work demonstrates that adding a lightweight cryptographic overlay at the application layer provides unique advantages. It strengthens replay resistance, enables metadata integrity, and decouples security from specific transport implementations. The combination of these factors makes the scheme not just a theoretical exercise but a pragmatic solution ready to be deployed in production-grade distributed applications [7].

7. Conclusions

This paper has presented a practical and reproducible model for securing data exchange between Python applications using a hybrid cryptographic approach. The central contribution of the work is the demonstration that strong security guarantees can be achieved with minimal complexity by carefully combining symmetric and asymmetric techniques in a layered manner. By leveraging X25519 for ephemeral key exchange together with HKDF for secure session key derivation, the system establishes fresh and unpredictable session keys for each communication. Once the handshake is complete, AES-GCM provides efficient, authenticated encryption of the message stream, ensuring both confidentiality and integrity. Digital signatures with Ed25519 protect the handshake itself, establishing the authenticity of the participants and preventing impersonation or man-in-the-middle interference. Additional authenticated data (AAD), which binds protocol versions, session identifiers, and sequence numbers into every encrypted message, ensures that metadata is tamper-proof and that replay or downgrade attacks cannot succeed.

The experimental evaluation confirmed that these security properties are achieved with only minimal performance cost. Encryption and decryption of medium-sized messages consistently required less than a millisecond, while asymmetric operations such as X25519 key exchange and Ed25519 signing or verification added only a few milliseconds to the initial session setup. Such results make the scheme feasible not only for server-grade systems but also for latency-sensitive applications such as real-time monitoring tools, microservice architectures, or IoT environments. Importantly, the measurements demonstrate that the computational burden of cryptography is no longer a limiting factor. Instead, the bottlenecks in distributed systems continue to lie in network latency and application logic, which means that the adoption of robust end-to-end security need not come at the expense of usability or responsiveness.

Beyond raw performance, the work highlights the accessibility of advanced cryptography in modern programming environments. Python, with its mature libraries like cryptography and PyNaCl, allows developers to implement secure communication channels with only a handful of lines of code. This democratization of cryptographic tools is significant because it lowers the barrier for organizations to adopt best practices. Even teams without dedicated cryptography experts can embed protection directly into their applications, reducing the risk of costly vulnerabilities caused by ad hoc or improvised security mechanisms [1,2].

The broader implication is that security should not be viewed exclusively as a responsibility of the network transport layer. While TLS remains indispensable as a general-purpose mechanism for securing communication over the internet, this study shows that embedding cryptographic guarantees at the application layer provides important complementary benefits. By operating directly on application-level messages, the scheme ensures that security persists even when data passes through intermediate brokers, message queues, or file-based exchanges. This end-to-end protection model aligns with modern trends such as zero-trust networking and microservice-based architectures, where the assumption of a trusted network perimeter is no longer realistic.

Looking toward the future, the presented model provides a foundation upon which further advancements can be built. One promising direction is the integration of post-quantum cryptographic algorithms, such as Kyber for key exchange and Dilithium for digital signatures, which would future-proof the scheme against the emerging threats of quantum computing. Another direction involves coupling the protocol with centralized key management systems (KMS). By doing so, key rotation and auditing could be automated, ensuring compliance with strict regulatory frameworks such as GDPR or HIPAA while reducing the administrative burden on developers. Finally, enriching the model with built-in monitoring, logging, and anomaly detection mechanisms would enhance operational visibility, making it easier to detect unusual patterns of communication that could indicate an attempted attack.

In summary, this work demonstrates that secure communication between Python applications can be achieved with a lightweight yet powerful cryptographic scheme. It proves that the combination of modern primitives, minimal implementation complexity, and efficient performance characteristics makes it possible to integrate end-to-end protection into distributed systems without disrupting their operation. The proposed model not only addresses today’s challenges of confidentiality, authenticity, and integrity but also offers a path toward adaptation in the face of tomorrow’s evolving cybersecurity landscape.

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ВІДОМОСТІ ПРО АВТОРІВ/ ABOUT THE AUTHORS

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ЗАХИСТ КАНАЛІВ ОБМІНУ ДАНИМИ МІЖ PYTHON-ЗАСТОСУНКАМИ ЗА ДОПОМОГОЮ КРИПТОГРАФІЧНИХ БІБЛІОТЕК

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Анотація. Актуальність. Зростаюча залежність від розподілених застосунків актуалізує потребу у створенні захищених каналів обміну даними між програмними компонентами. Без належного захисту комунікація стає вразливою до атак, таких як перехоплення, підміна, модифікація та повторна відправка повідомлень. **Предметом дослідження** у статті є використання криптографічних бібліотек Python (cryptography, PyNaCl) для побудови легких, але надійних механізмів безпеки поверх наявних каналів обміну. **Метою статті** є представлення практичного та відтворюваного методу захисту інформаційних потоків шляхом поєднання симетричного шифрування (AES-GCM), ефемерного обміну ключами (X25519), виведення ключів (HKDF із SHA-256) та цифрових підписів (Ed25519). **Були отримані наступні результати.** Запропонована модель інтегрує аутентифіковане шифрування з додатковими даними (AEAD) та лічильниками повідомлень для запобігання повторним атакам, залишаючись сумісною з різними транспортними рівнями (HTTP, gRPC, MQTT). У роботі наведено мінімальні приклади коду та результати вимірювань продуктивності, які показують, що шифрування та розшифрування займають менше однієї мілісекунди для типових повідомлень, а обмін ключами та операції підпису додають лише кілька мілісекунд. Це свідчить про можливість реалізації потужного криптографічного захисту без значних накладних витрат. **Висновок.** Отримані результати підтверджують, придатність схеми для розподілених систем у режимі реального часу, мікросервісів та IoT. Подальший розвиток може включати інтеграцію постквантових алгоритмів та автоматизоване управління ключами.

Ключові слова: Python-застосунки; захищена комунікація; AES-GCM; X25519; Ed25519; HKDF; захист від replay-атак.