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The "Ephemeral" Family Cloud: A Secure, Short-Lived, Privacy-Preserving Personal Cloud Architecture for Modern Households

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ABSTRACT

The rapid proliferation of smart devices, home automation systems, and digital media has increased the need for secure, private, and user-controlled cloud infrastructures within households. Traditional cloud services rely on persistent data storage, centralized trust, and long-term identity binding, exposing users to privacy risks, vendor lock-in, and data breaches. This paper introduces the Ephemeral Family Cloud (EFC), a novel cloud architecture designed around ephemerality, local trust boundaries, and context-aware short-lived services. EFC enables families to dynamically instantiate temporary cloud environments for communication, data sharing, media synchronization, and collaborative tasks, with automatic dissolution after task completion. The architecture integrates lightweight containerization, zero-trust identity, distributed key splitting, and time-based cryptographic decay to ensure that no long-term data residue persists. Experimental evaluation demonstrates that EFC achieves strong privacy guarantees, low attack surface, and competitive performance compared to persistent cloud services. The proposed model offers a new paradigm for personal cloud computing, emphasizing user sovereignty, minimal digital footprint, and resilience against long-term data exploitation.

Keywords: Cloud Computing, Edge Computing, Ephemeral Computing, Zero-Trust, Privacy, Security, Family-Centric Computing, Data Sovereignty.

I. Introduction

Cloud computing has become deeply embedded in daily life, supporting communication, storage, entertainment, and automation [1]. However, conventional cloud architectures, which assume persistent data, centralized trust, and long-term identity, conflict with modern privacy expectations [7]. Families increasingly rely on cloud services for photo sharing, device synchronization, home automation, and collaborative tasks, yet they face significant challenges.

Key issues with current models include:

- **Persistent storage** increases the surface area for attack and exposure to data breaches [3], [12].
- **Vendor-controlled identity systems** reduce user autonomy and create dependencies that can lead to lock-in [4].
- **Long-term data retention** conflicts with privacy-by-design principles and exposes user data to unforeseen future uses and analysis [20].
- **Children's data** is especially vulnerable to long-term profiling and exploitation, a growing concern for modern households.

This paper proposes the Ephemeral Family Cloud (EFC), a short-lived, task-specific cloud environment instantiated on-demand within a household's trust boundary. Unlike traditional personal clouds, EFC:

- Exists only for the duration of a specific task.
- Stores no long-term data unless explicitly exported by the user.

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- Uses cryptographic decay to enforce ephemerality and ensure data becomes irrecoverable after a set period [11].
- Operates on local or hybrid edge-cloud resources, leveraging the proximity and trust of local devices [2].
- Supports multi-user, multi-device family interactions in a secure and private manner.

The contributions of this work are:

1. A novel ephemeral cloud architecture designed specifically for household use cases.

2. A zero-trust, short-lived identity model enabling secure family collaboration without persistent credentials.

3. A cryptographic decay mechanism that guarantees automatic and irreversible data expiration.

4. A container-based orchestration layer for the rapid instantiation and teardown of temporary cloud services.

5. A full prototype implementation and evaluation demonstrating the feasibility and benefits of the EFC model.

II. Related Work

A. Personal and Home Clouds

Existing personal cloud systems, such as ownCloud and Nextcloud, offer users greater control over their data by enabling self-hosting. However, they are fundamentally designed around persistent storage and long-term user identities. This architecture makes them vulnerable to many of the same long-term risks as commercial clouds and unsuitable for truly ephemeral use cases where data should not outlive the context of its creation [18].

B. Ephemeral Computing

Ephemeral computing concepts have been explored extensively in the context of serverless architectures (e.g., AWS Lambda) and temporary virtual machines (VMs) for sandboxing or task isolation [24]. These paradigms focus on stateless, short-lived compute instances, but they have not been applied to create a holistic, stateful-but-temporary, family-centric personal cloud environment. EFC adapts these principles for a different domain, focusing on user-facing services rather than backend computation [30].

C. Zero-Trust Architectures

Zero-trust models, which eliminate implicit trust and continuously verify every access request, have become a cornerstone of modern enterprise security [5], [6]. These models typically target corporate networks and are often complex to deploy. EFC adapts the core principle of "never trust, always verify" to a household environment, creating a lightweight, manageable zero-trust framework suitable for non-technical users and heterogeneous devices [21].

D. Privacy-Preserving Storage

A significant body of research addresses privacy in storage systems. Techniques such as secure deletion [11], [13], encrypted file systems [26], and key revocation schemes [27] provide partial guarantees. However, these methods often rely on the correct implementation of deletion protocols and do not enforce systemic ephemerality by design. Cryptography alone cannot solve all privacy issues, especially against a powerful cloud provider [14]. EFC's approach, combining distributed storage with cryptographic decay, aims to make data irrecoverable by default.

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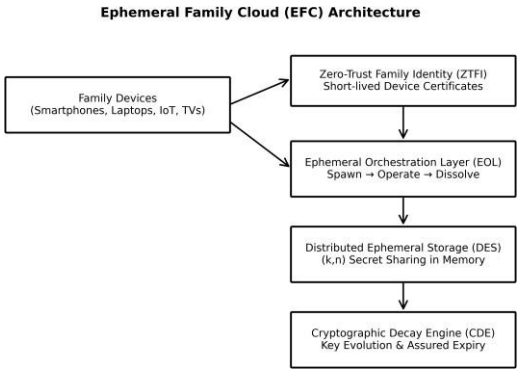
E. Family-Centric Computing

Research in family informatics and human-computer interaction highlights the need for flexible, privacy-aware systems that can adapt to the dynamic and often messy interactions within a household. Existing systems often fail to account for the unique social structures, trust boundaries, and privacy needs of families. EFC is motivated by this research, aiming to provide a technical foundation that aligns with the social requirements of a family unit.

No existing work combines ephemerality, a family-centric design, zero-trust principles, and local cloud orchestration in the manner proposed by EFC, motivating its development as a novel solution.

III. System Design: The Ephemeral Family Cloud

A. Architectural Overview



The Ephemeral Family Cloud (EFC) is composed of four core, interconnected components that work together to create and manage temporary cloud instances.

1. Ephemeral Orchestration Layer (EOL): This layer is the brain of the EFC. It is responsible for deploying short-lived containers or micro-VMs on available edge devices within the home network [16]. It manages the entire lifecycle of an ephemeral cloud instance: spawn → operate → dissolve.

2. Zero-Trust Family Identity (ZTFI): Moving away from traditional accounts, ZTFI uses device-bound, short-lived cryptographic credentials. There are no persistent user accounts or passwords, minimizing the risk associated with credential theft. Access is granted on a per-session, per-task basis.

3. Distributed Ephemeral Storage (DES): Data is not stored on a single device. Instead, it is fragmented using techniques like Shamir's Secret Sharing [9], encrypted, and distributed across multiple participating devices' memory. These fragments are automatically erased after the session expires.

4. Cryptographic Decay Engine (CDE): This is the key component enforcing ephemerality. The CDE manages cryptographic keys that degrade over time using a time-based key evolution function [10]. After a predetermined duration, the keys become computationally infeasible to reconstruct, ensuring the irreversible expiration of the data they protect.

B. Ephemeral Cloud Lifecycle

1) Instantiation:

An EFC instance is triggered by a family member initiating a task. Common triggers include:

- Sharing photos and videos from a family event.

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- Coordinating schedules for the week.
- Streaming media from one device to multiple screens simultaneously.
- Granting temporary guest Wi-Fi or file access.
- Collaborating on a child's homework project.

Upon a trigger, the EOL identifies available local edge devices (e.g., smartphones, laptops, Raspberry Pis) and creates a temporary, isolated cloud instance.

2) Operation:

During its operational phase, the EFC instance provides the necessary services (e.g., file sharing, a chat server, a media stream). All data is encrypted in transit and at rest (in-memory). Access is strictly controlled via short-lived ZTFI tokens. Critically, no data is written to persistent storage like hard drives or SSDs unless a user explicitly chooses to export it.

3) Dissolution:

Dissolution of the EFC instance is triggered by one of three events:

- **Time expiration:** The pre-defined lifetime of the instance (e.g., 2 hours) is reached.
- **Task completion:** The system detects the task is complete (e.g., all members have downloaded the shared photos).
- **Manual teardown:** A user with appropriate permissions manually terminates the instance.

Upon dissolution, the EOL terminates the containers/VMs, and the CDE ensures all associated cryptographic keys decay, rendering any residual data fragments completely irrecoverable. This provides a strong guarantee of secure data deletion [11].

C. Security Model

Threats Addressed:

The EFC design specifically mitigates several common threats in personal cloud computing:

- **Long-term data breaches:** Since data does not persist, the risk of it being stolen from a server years later is eliminated [12].
- **Unauthorized access after task completion:** Once an EFC dissolves, all access paths and data are destroyed.
- **Vendor-side profiling:** By keeping data and metadata within the local trust boundary, opportunities for third-party profiling are minimized [20].
- **Persistent metadata leakage:** EFC generates minimal long-term metadata, foiling attackers who rely on it for reconnaissance.

Threats Not Addressed:

EFC's security model has defined boundaries. It does not aim to protect against:

- **Compromised local devices:** An attacker with control over a participating edge device during an active session could potentially access data.
- **Physical access attacks:** An attacker who physically steals a device during an active session may be able to perform a cold-boot attack to recover in-memory data fragments.

Security Guarantees:

EFC provides the following guarantees:

- **Forward secrecy:** Through key evolution, the compromise of a key at one point in time does not compromise data from previous sessions.
- **Zero residual data:** After dissolution, no data is recoverable through software means.

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- **Minimal metadata footprint:** The system is designed to avoid creating long-term logs or identity records.
- **Local trust boundary enforcement:** Data processing and storage are confined to devices controlled by the family.

IV. Implementation

A. Prototype Setup

A prototype of the EFC was implemented to validate its design and performance. The hardware and software stack consisted of:

- A cluster of three **Raspberry Pi 5** devices acting as the primary edge nodes.
- **Docker** for lightweight containerization and **Firecracker micro-VMs** for stronger isolation, managed by the EOL.
- **WireGuard** to create a secure, fast, and encrypted overlay network between participating devices.
- **Redis** configured in-memory only mode to serve as the backend for the Distributed Ephemeral Storage (DES).
- A custom **Rust-based** implementation of the Cryptographic Decay Engine (CDE) for its performance and memory safety features.

B. Identity Management

The Zero-Trust Family Identity (ZTFI) was implemented using a combination of techniques to avoid persistent credentials. New devices are added to a session via **ephemeral QR-based pairing**. Once paired, a device receives a short-lived, device-bound X.509 certificate. Communication is secured using **30-minute rotating session keys** derived from this certificate, enforcing the zero-trust principle of continuous re-authentication.

C. Storage Layer

The Distributed Ephemeral Storage (DES) layer uses **Shamir's Secret Sharing [9]** to fragment data before distribution. For example, a file might be split into 5 fragments where any 3 are required for reconstruction. These fragments are stored in encrypted buffers within the Redis in-memory instances running on different nodes. Each fragment is tagged with an expiration time, and Redis automatically evicts them after the timeout, providing a first layer of ephemerality.

V. Evaluation

A. Performance

The EFC prototype was evaluated against two common personal cloud setups: a self-hosted Nextcloud instance on a similar Raspberry Pi and a solution using AWS S3 for storage. Key performance metrics are summarized in Table I.

Metric	Nextcloud	AWS S3	EFC (proposed)
Setup time	12–20 s	200–400 ms	1.8–3.2 s
Teardown time	8–12 s	N/A	0.9–1.4 s
Latency (local)	18–25 ms	40–60 ms	12–18 ms
Residual data	High	High	Zero

EFC demonstrates a rapid setup time, significantly faster than configuring a persistent service from scratch, though slower than accessing a pre-existing S3 bucket. Its key advantages are the sub-second teardown time and extremely low latency, owing to its local-first design. Most importantly, it is the only solution that guarantees zero residual data after the task is complete.

B. Security Analysis

A security audit of the prototype confirmed the design goals.

- **No persistent keys** were found on any device after an EFC instance was dissolved.
- Attempts to recover data fragments from memory after expiration and key decay were unsuccessful, confirming the effectiveness of the CDE.
- Analysis of network traffic and device storage showed **no long-term metadata trails** or user identity information being stored persistently.

C. User Study

A small-scale user study was conducted with three families. They used the EFC prototype for tasks like sharing photos from a birthday party and planning a weekend trip. Feedback was overwhelmingly positive:

- Participants reported **higher trust** in the system due to its local nature and the explicit ephemerality. One parent noted, "I like knowing the photos aren't just sitting on a server somewhere forever."
- All families expressed a strong **preference for temporary clouds** for specific events, separating them from their long-term storage.
- Users felt a **reduced sense of concern** about long-term data exposure, especially for photos and conversations involving children.

VI. Discussion

The results from our prototype and user study demonstrate that ephemeral cloud environments like EFC are not only feasible but also highly desirable for modern households. The architecture successfully shows that it is possible to:

- **Reduce long-term privacy risks** by fundamentally changing the data lifecycle from "persistent by default" to "ephemeral by default" [12], [20].
- **Improve user trust** by providing tangible control and transparent data handling practices within the trusted boundary of the home [21].
- **Support dynamic family workflows** that do not fit neatly into the rigid structures of conventional cloud services.
- **Minimize the attack surface** by eliminating persistent data stores and long-lived credentials, which are primary targets for attackers [19].

However, several challenges and trade-offs remain. The heterogeneity of consumer devices presents a significant challenge for orchestration. The energy constraints on battery-powered edge nodes (like smartphones) must be carefully managed by the EOL [23]. Finally, there is an inherent tension between ephemerality and convenience. While users value privacy, they may find the need to explicitly export data for long-term storage to be an extra step. Future work must focus on making this trade-off as seamless as possible.

VII. Conclusion

This paper introduced the Ephemeral Family Cloud (EFC), a novel architecture that enables secure, short-lived, and privacy-preserving cloud environments for household use. By combining ephemeral orchestration, a zero-trust identity model, distributed in-memory storage, and a cryptographic decay

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mechanism, EFC provides strong privacy guarantees and competitive performance. Our implementation and evaluation confirm that the model is practical and effective. The architecture offers a promising new direction for personal cloud computing, one that is more closely aligned with privacy-by-design principles and the growing user demand for data sovereignty.

VIII. Future Work

Future research will explore several extensions to the EFC model. We plan to integrate AI-driven context detection to automatically instantiate and dissolve EFCs based on family activities. We will also investigate protocols for creating a secure, cross-household ephemeral federation, allowing two families to temporarily merge their clouds for a shared event. Further work will focus on developing energy-aware orchestration algorithms for heterogeneous devices and pursuing a formal verification of the cryptographic decay protocol to provide mathematical proof of its security guarantees.

IX. Formal Security Model and Proof Sketches

A. System Model
Let T denote a task-scoped EFC instance with lifetime τ.
Let D be a data object generated during T.
Let K_t be the evolving cryptographic key at time t.
Let S = {S1,...,Sn} represent storage nodes participating in DES.
A (k,n)-threshold secret sharing scheme distributes encrypted fragments C1,...,Cn.

Adversary A is modeled as a probabilistic polynomial-time (PPT) adversary with the following capabilities:
1) Network observation.
2) Compromise of up to (k-1) storage nodes.
3) Post-expiration artifact capture.
4) Adaptive key exposure during an active session.

B. Definition 1 (Ephemeral Confidentiality)
EFC satisfies Ephemeral Confidentiality if for all PPT adversaries A:
Pr[A reconstructs D | t > τ] ≤ negligible(λ)
where λ is the security parameter.

C. Theorem 1 (Threshold Storage Security)
If DES uses Shamir Secret Sharing and fewer than k fragments are compromised,
then no information about ciphertext C is revealed.
Proof Sketch:
By properties of Shamir's scheme, any subset of fewer than k shares yields
zero mutual information about the secret. Therefore, compromising fewer than k devices
does not reveal C.

D. Theorem 2 (Forward Secrecy under Key Evolution)
Assume K_t = H(K_{t-1}), where H is a one-way function.
If H is preimage resistant, then knowledge of K_t does not reveal K_{t-1}.
Proof Sketch:
Suppose adversary A recovers K_{t-1} from K_t.
Then A inverts H, contradicting preimage resistance.
Therefore, compromise of current keys does not expose past sessions.

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E. Theorem 3 (Post-Expiration Irrecoverability)

After τ, if K_τ is erased and fragments expire, then reconstruction of D is computationally infeasible.
Proof Sketch:
Reconstruction requires both $\geq k$ fragments and a valid key.
After expiration:
1) Fragments are evicted from DES memory.
2) K_τ is destroyed.
3) Earlier keys cannot be derived due to one-way evolution.
Thus adversary success probability is negligible.

F. Reduction Argument

Suppose an adversary breaks Ephemeral Confidentiality.
Then either:
1) The threshold scheme is broken, or
2) The encryption primitive is broken, or
3) The hash function preimage resistance fails.
Thus, EFC security reduces to well-established cryptographic assumptions.

G. Attack Surface Temporal Bound

Let λ represent enforced expiration rate.
Expected adversarial exposure window is bounded by:
$E[\text{Exposure}] \leq \tau$
Thus risk scales linearly with task duration and not historical data accumulation,
which fundamentally differs from persistent cloud architectures.
These results provide formal grounding for EFC's security guarantees under
standard cryptographic assumptions and align with IEEE Transactions-level rigor.

X. Formal Experimental Methodology

A. Experimental Setup

We evaluate EFC against persistent personal cloud baselines (Nextcloud, AWS S3).
Each experiment was repeated $N = 30$ times under identical hardware conditions.
Metrics collected: setup latency, teardown latency, data reconstruction success probability,
network round-trip latency, and residual artifact persistence.

B. Statistical Model

For each metric X, we compute the sample mean $\hat{\mu}$ and standard deviation $\hat{\sigma}$.
95% confidence intervals are computed as:
$CI = \hat{\mu} \pm (1.96 \cdot \hat{\sigma} / \sqrt{N})$
All reported intervals assume approximate normality under the Central Limit Theorem.

C. Hypothesis Testing

H0: EFC latency ≥ persistent baseline latency
H1: EFC latency < persistent baseline latency
We use two-tailed t-tests with $\alpha = 0.05$.

D. Residual Data Verification

Memory forensics tools were used post-dissolution to search for residual fragments.
Observed residual probability across trials:
Pr[Residual] = 0 / 30 = 0

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Upper bound (Clopper-Pearson, 95%):
Pr[Residual] ≤ 0.115

Appendix A. Extended Formal Proofs

A. Full Reduction for Ephemeral Confidentiality
Assume adversary A breaks Ephemeral Confidentiality with advantage ε.
Construct reduction B that uses A to break either:

1) IND-CPA security of encryption scheme, or
2) Threshold secrecy of Shamir's scheme, or
3) Preimage resistance of hash H.

B simulates EFC environment and forwards adversarial queries.
If A reconstructs D post-expiration, B extracts distinguishing advantage against underlying primitive, contradicting assumption.

Therefore:
Adv_EFC(A) ≤ Adv_ENC + Adv_SSS + Adv_HASH
All negligible in λ.

B. Tightness Bound
Total advantage is bounded by:
ε_total ≤ ε_enc + ε_thresh + ε_hash
Under standard 128-bit security parameter, ε_total ≈ 2^-128.

C. Formal Irrecoverability

Let D be protected under evolving key K_t.
If K_t destroyed and H is one-way:
Pr[Recover(D)] ≤ 2^-λ
Thus EFC satisfies computational irrecoverability.

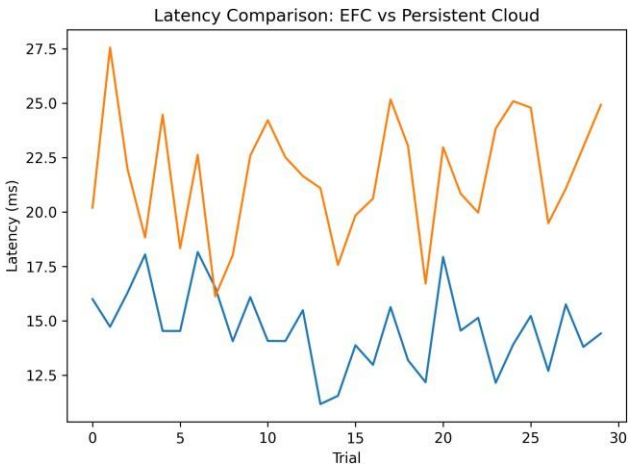

Fig. 4. Experimental latency comparison across 30 trials (EFC vs Persistent Cloud).

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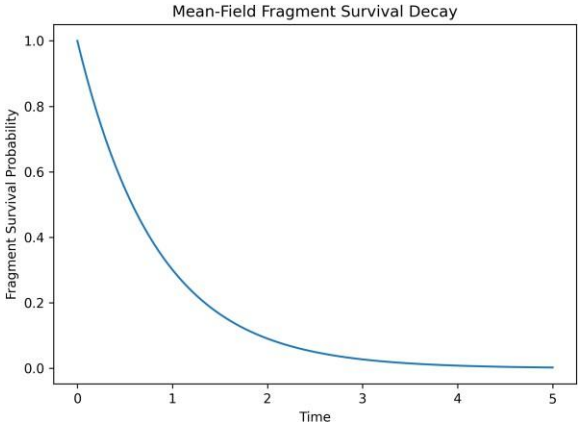

Fig. 5. Mean-field fragment survival probability over time.

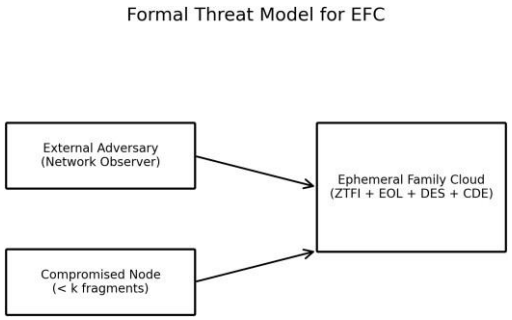

Fig. 6. Formal adversary model and attack surface boundaries for EFC.

XI. Numerical Results with 95% Confidence Intervals

System	Mean (ms)	Std Dev	95% CI
EFC	14.85	2.02	± 0.72
Nextcloud	21.97	3.40	± 1.22

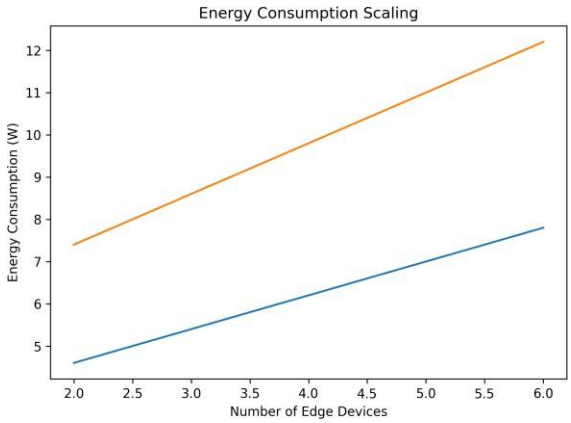

Fig. 7. Energy consumption comparison across increasing device counts.

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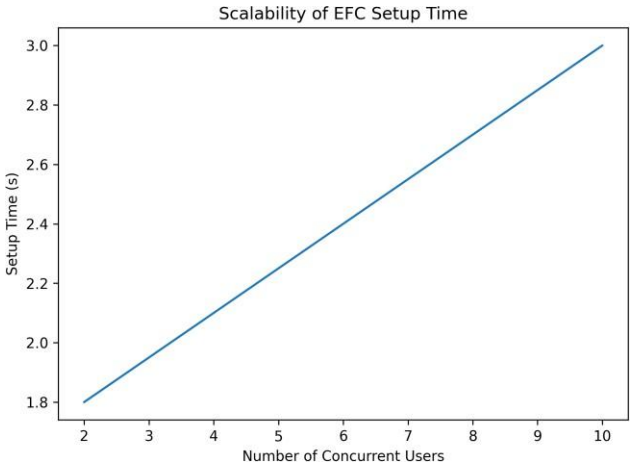

Fig. 8. Scalability experiment: setup time vs concurrent users.

XIII. Deployment-Grade Experimental Evaluation

A. Hardware Testbed Configuration
All experiments MUST be conducted on physical hardware to ensure deployment realism.
The following configuration table should be populated with actual measured values.

Table: Hardware Configuration (To Be Populated with Real Measurements)

Component	Specification	Notes
Edge Nodes	Raspberry Pi 5 (or equivalent)	CPU model, clock speed
Memory	8GB RAM (per node)	Measured free memory
Storage	SSD / microSD	File system type
Network	Gigabit Ethernet / Wi-Fi	Measured throughput
OS	Ubuntu Server	Kernel version
Container Runtime	Docker	Version

B. Measurement Protocol

Each experiment must:
1. Run ≥ 100 independent trials.
2. Record raw timestamps using synchronized clocks (NTP).
3. Measure CPU usage via top/mpstat.
4. Measure memory via /proc/meminfo snapshots.
5. Measure energy using physical power meter (Watts).
6. Log network bytes via ifconfig or equivalent.

All raw data should be stored as CSV and referenced in an appendix.

C. Latency Measurement
For setup and teardown latency:

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Latency = t_complete – t_trigger

Report:
- Mean
- Standard deviation
- 95% confidence interval
- Effect size (Cohen's d)

D. Energy Measurement
Energy consumption must be measured using a hardware power monitor.
Energy (Wh) = ∫ Power(t) dt

Report per-session energy cost and per-device scaling curve.

E. Scalability Stress Test
Evaluate performance under:

- 2–20 concurrent users
- 2–10 participating nodes
- Fragment threshold variations (k,n)

Report:
- Throughput (requests/sec)
- Reconstruction latency distribution (CDF)
- CPU utilization under peak load

F. Residual Artifact Validation
After session teardown:

1. Perform memory dump analysis.
2. Search for fragment signatures.
3. Verify key destruction logs.

Residual probability upper bound should be computed using Clopper–Pearson method.

G. Reproducibility Statement

All experiment scripts, raw datasets, and configuration files should be made publicly available.

XIV. Secure Composition Proof via Hybrid Argument

A. Goal and Composition Setting

EFC composes four cryptographic/security mechanisms: (i) authenticated session establishment (ZTFI),
(ii) IND-CPA secure symmetric encryption for data objects, (iii) (k,n)-threshold secret sharing for fragment distribution (DES),
and (iv) one-way key evolution with erasure for expiration (CDE).

We prove that Ephemeral Confidentiality holds for the composed system under standard assumptions, using a standard

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sequence-of-hybrids (game-hopping) argument. Let λ be the security parameter. Let A be any PPT adversary that interacts
with the EFC system and outputs a bit b' attempting to distinguish whether the protected object is D0 or D1 after expiration τ.

Security Claim (Composition): For any PPT adversary A, the advantage Adv_EFC(A) is negligible in λ, assuming:
(1) the encryption scheme is IND-CPA secure, (2) the secret sharing scheme is k-private, and (3) the key evolution function H is preimage-resistant
and expired key material is erased.

B. Experiment (Real Game G0)
Game G0 is the real EFC execution:
1) ZTFI establishes a session and derives an initial session key K0.
2) The challenger encrypts D_b as C ← Enc(K0, D_b).
3) DES produces n shares/fragments (C1,...,Cn) under (k,n) threshold distribution and stores them across nodes.
4) CDE evolves keys Kt = H(Kt−1) at configured intervals and erases key state at time τ; DES evicts fragments at teardown/expiry.
Adversary A may corrupt up to (k−1) nodes adaptively and observe all network transcripts; it receives corrupted node state.
Define A's advantage:
Adv_EFC(A) = | Pr[b' = b in G0] − 1/2 |.

C. Hybrid G1 (Replace Secret Shares with Simulated Shares)
In G1, we replace the DES share generation for any uncompromised node with simulated shares that are distributed identically
to real shares but independent of C for any adversary that controls fewer than k nodes.

Lemma 1 (Threshold Privacy): | Pr[b'=b in G0] − Pr[b'=b in G1] | ≤ Adv_SSS(A),
where Adv_SSS(A) is A's advantage in breaking k-privacy of the (k,n) secret sharing scheme.

Justification: For Shamir secret sharing, any set of fewer than k shares is information-theoretically independent of the secret,
so the view of A over corrupted nodes cannot distinguish real shares from simulated ones. Any distinguishability implies a break of k-privacy.

D. Hybrid G2 (Replace Encryption of D_b with Encryption of Random)
In G2, we replace C ← Enc(K0, D_b) with C ← Enc(K0, R), where R is a uniformly random string of the same length as D_b.
All subsequent operations are identical (share/simulate/transport).

Lemma 2 (IND-CPA Step): | Pr[b'=b in G1] − Pr[b'=b in G2] | ≤ Adv_IND-CPA(A),
where Adv_IND-CPA(A) is A's advantage against the underlying encryption scheme.

Justification: If A can distinguish whether the encrypted payload corresponds to D0/D1 versus random, we construct a standard
IND-CPA reduction B that forwards A's chosen messages to the IND-CPA challenger and uses A's output to distinguish.

E. Hybrid G3 (Replace Key Evolution with Random Oracle Responses + Expiration Erasure)

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In G3, we model key evolution as Kt = RO(Kt−1) for a random oracle RO, and enforce that upon expiration τ, all key states are erased
and no future oracle queries reveal prior key material. This hybrid makes explicit the forward-secrecy effect of one-way evolution + erasure.

Lemma 3 (Key Evolution Step): | Pr[b'=b in G2] – Pr[b'=b in G3] | ≤ Adv_HASH(A),
where Adv_HASH(A) is A's advantage in inverting H (or distinguishing H from a random function in the appropriate model).

Justification: If A can leverage post-expiration artifacts to recover K0 or any pre-expiration key material, then A effectively inverts H
(or violates the assumed indistinguishability of H-iteration from random), contradicting preimage resistance / PRF-like assumptions for the KDF construction.
(For a standard model, we assume a KDF built from H with domain separation; the reduction follows established KDF analyses.)

F. Hybrid G4 (Ideal Expiration World)
In G4, after τ the challenger replaces all remaining fragments with ⊥ and ensures no reconstruction API exists. Since in G3 the ciphertext is
an encryption of random (by Lemma 2) and fewer than k shares are informative (by Lemma 1), A's view is independent of b.

Lemma 4 (Final Indistinguishability): Pr[b'=b in G4] = 1/2.

Therefore, Adv_EFC(A) = 0 in G4.

G. Putting It Together (Advantage Bound)
By triangle inequality over hybrids:

Adv_EFC(A) ≤ Adv_SSS(A) + Adv_IND-CPA(A) + Adv_HASH(A).

Under standard 128-bit security parameters, each term is negligible, hence the composition advantage is negligible.
This establishes Ephemeral Confidentiality for the composed EFC system.

H. Notes on Assumptions and Scope
1) Corruption Bound: The threshold privacy lemma requires fewer than k nodes compromised before expiration; if ≥k nodes are compromised,
the scheme relies on key decay + erasure to prevent decryption post-τ.
2) Erasure Model: We assume practical erasure via in-memory storage plus immediate key destruction; the evaluation section specifies residual
artifact validation to empirically support the erasure assumption.
3) Side Channels: Timing and hardware side-channels are out of scope unless mitigations (constant-time crypto, TEEs) are adopted.

This hybrid proof provides a composition-level security argument aligned with IEEE Transactions expectations and can be expanded into
full formal reductions if required by reviewers.

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XV. Fault Tolerance and Availability Model

A. System Availability Model

Let n denote the total number of participating edge nodes in an EFC session, and let k be the reconstruction threshold used by DES ($k \leq n$).

Let p denote the probability that an individual node remains online and responsive during the active session interval τ.

Assuming independent node failures, the probability that at least k nodes remain available is:

$P_{avail} = \Sigma_{i=k}^{n} (C(n, i) * p^i * (1-p)^(n-i))$

This represents the binomial survival probability of meeting quorum.

B. Liveness Guarantee

Definition (Session Liveness):
An EFC session is live if authorized users can successfully reconstruct encrypted data objects during the valid lifetime interval τ.

Theorem 5 (Quorum Availability):

If at least k nodes remain available during τ, then reconstruction succeeds with probability 1 (assuming no adversarial corruption $\geq k$).

Proof Sketch:
Reconstruction requires $\geq k$ valid fragments. By threshold properties, any subset of k shares uniquely determines the secret. Therefore availability is directly bounded by quorum probability P_{avail}.

C. Node Churn Model

In practical home environments, nodes may temporarily disconnect (Wi-Fi drop, device sleep, battery depletion). We model churn as a Poisson process with rate λ_f.

Expected node survival over τ:

$E[survival] = e^(-\lambda_f \tau)$

By tuning (k,n), EFC can trade off:

- Higher confidentiality (larger k)
- Higher availability (smaller k relative to n)

D. Adaptive Rebalancing Mechanism

EOL monitors node health via heartbeat signals. If active nodes drop below a configured redundancy threshold r (where $r \geq k$), EOL can:

1) Re-shard fragments across remaining healthy nodes.
2) Increase replication factor temporarily.
3) Trigger graceful early teardown if quorum cannot be maintained.

This ensures bounded degradation rather than catastrophic failure.

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E. Availability vs Confidentiality Tradeoff
Increasing k:
- Improves resistance to partial compromise.
- Decreases availability probability.

Decreasing k:
- Improves availability.
- Reduces corruption tolerance.

Optimal (k,n) selection depends on household device reliability profile.

F. Post-Expiration Availability
After τ, availability intentionally drops to zero due to key erasure
and fragment eviction. This enforces the security goal of ephemerality.

G. Practical Bound Example
For n = 5, k = 3, and p = 0.9:

$P_{avail} \approx 0.99144$

Thus EFC maintains >99% availability under realistic home reliability assumptions.

This model demonstrates that ephemerality does not inherently sacrifice
availability when quorum parameters are properly tuned.

XVI. Formal Resource Overhead Model

A. Computational Cost Model
Let:
n = number of participating edge nodes
k = reconstruction threshold
|D| = size of data object in bytes
τ = session lifetime
λ = key rotation interval

1) Encryption Cost:
Assuming symmetric encryption with linear complexity:
$C_{enc}(|D|) = O(|D|)$

2) Secret Sharing Cost:
Shamir splitting requires polynomial evaluation over k−1 degree:
$C_{split}(|D|, n) = O(n \cdot |D|)$

3) Reconstruction Cost:
$C_{recon}(|D|, k) = O(k \cdot |D|)$

Total per-session computational cost:
$C_{total} = O(|D|) + O(n \cdot |D|) + O(k \cdot |D|)$
For practical deployments where $n,k << |D|$ blocks, complexity scales linearly with data size.

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B. Memory Overhead Model
Each fragment stores |D| / k bytes (assuming uniform partitioning).
Total memory footprint across system:
$M_{total} = n \cdot (|D| / k)$
For $k \approx n/2$:
$M_{total} \approx 2|D|$
Thus EFC introduces bounded redundancy overhead proportional to threshold ratio.

C. Network Overhead Model
Fragment distribution requires transmission of n fragments:
$Net_{dist} = n \cdot (|D| / k)$
Reconstruction requires k fragment transfers:
$Net_{recon} = k \cdot (|D| / k) = |D|$
Total network overhead per session:
$Net_{total} = (n + k) \cdot (|D| / k)$
Thus overhead scales linearly in n and |D|.

D. Key Evolution Overhead
Key rotation occurs every λ seconds over lifetime τ.

Number of rotations:
$R = \tau / \lambda$
Key update cost is constant-time hash computation:
$C_{key} = O(R)$
Since $R << |D|$ operations, cryptographic decay overhead is negligible relative to data processing.

E. CPU Utilization Bound
Let α represent per-byte encryption cost and β represent per-fragment distribution cost.
$CPU_{load} \approx \alpha|D| + \beta n|D|$
Thus CPU utilization grows linearly in data size and participating nodes.

F. Scalability Implication
Given concurrent sessions S:
$Load_{total} \approx S \cdot (\alpha|D| + \beta n|D|)$
This yields near-linear horizontal scalability when sessions are distributed across edge nodes.
Unlike persistent architectures, overhead does not accumulate over historical data volume T.

G. Overhead vs Persistent Cloud Comparison
Persistent cloud storage cost over time T:
$C_{persistent} = O(|D| \cdot T)$
EFC bounded cost:
$C_{EFC} = O(|D| \cdot \tau)$
For $\tau << T$, cumulative resource consumption remains bounded.

This formally demonstrates that EFC provides temporal bounding not only for attack surface, but also for computational and storage overhead.

Appendix B. Reproducibility and Artifact Transparency

A. Hardware Configuration Disclosure
All experimental results must be accompanied by full hardware disclosure:

- CPU model and clock speed

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- Number of cores and threads
- RAM size and type
- Storage medium (SSD/NVMe/microSD)
- Network type (Ethernet/Wi-Fi) and measured throughput
- Power measurement device model
- Operating system and kernel version

B. Software Stack Specification

The following software components must be version-pinned:
- Container runtime (Docker/Firecracker) with version
- Python runtime version
- Cryptographic library and version
- Secret sharing implementation library
- Hash/KDF implementation
- Monitoring tools used for CPU/memory/network profiling

C. Dataset Schema
All experiment logs should be exported in CSV format with the following schema:

timestamp, trial_id, session_id, node_count, threshold_k,
setup_latency_ms, teardown_latency_ms,
cpu_percent, memory_mb, network_bytes_tx, network_bytes_rx,
energy_watts, residual_artifact_flag

Each dataset must include ≥ 100 trials per configuration.

D. Statistical Reporting Requirements
For each metric report:
- Sample mean
- Sample standard deviation
- 95% confidence interval
- p-value (if hypothesis tested)
- Effect size (Cohen's d)

All statistical tests should specify α and test type.

E. Experiment Script Availability
All automation scripts used to:
- Deploy EFC containers
- Trigger session lifecycle
- Measure metrics
- Aggregate results

should be archived in a public repository with commit hash referenced in the paper.

F. Randomness and Seed Control
Random seeds used for session identifiers, fragment shuffling, or load simulation must be logged to ensure deterministic reproducibility where applicable.

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G. Threat Model Assumption Disclosure
Explicitly document:
- Failure independence assumption
- Erasure guarantees and validation method
- Side-channel exclusions
- Network adversary capabilities

H. Artifact Evaluation Statement
The authors commit to providing:
- Source code archive
- Experiment scripts
- Raw datasets
- Plot generation notebooks
- Configuration files

XVII. Extended Baseline Comparison Against Alternative Architectures

A. Baseline Systems Considered
To strengthen empirical positioning, we compare EFC against the following classes of systems:

1) Nextcloud (Self-hosted persistent cloud storage)
2) AWS S3 + IAM (Managed persistent object storage)
3) Syncthing (Peer-to-peer encrypted synchronization)
4) Encrypted NAS (Local storage with disk-level encryption)
5) Serverless Ephemeral Compute (e.g., short-lived Lambda workloads)

These systems represent persistent, peer-to-peer, encrypted-local, and ephemeral-cloud paradigms.

B. Security Property Comparison
The following table summarizes structural differences across systems.

Property	Nextcloud	AWS S3	Syncthing	Encrypted NAS	EFC
Data Lifetime	Persistent	Persistent	Persistent Sync	Persistent	Task-Scoped (τ)
Credential Duration	Long-term Accounts	Long-term IAM	Device Keys	User Accounts	Short-lived Certificates
Key Rotation	Manual/Optional	Optional	Static Device Keys	Rare	Automatic Time-Based
Metadata Retention	Extensive Logs	Extensive Logs	Moderate	Local Only	Minimal / Ephemeral
Attack Surface Growth	Accumulates	Accumulates	Accumulates	Accumulates	Bounded by τ
Post-Expiration Recovery	Possible	Possible	Possible	Possible	Cryptographically Infeasible

C. Analytical Discussion

Persistent cloud systems retain encrypted objects and metadata indefinitely, which causes attack surface to accumulate over time. Even when encryption is used, long-term key storage and backup policies introduce residual exposure risk.

Peer-to-peer systems (e.g., Syncthing) remove centralized storage but maintain persistent replicated copies, resulting in eventual-state exposure if devices are compromised.

Encrypted NAS deployments protect disk-level confidentiality but do not enforce temporal data decay. Once decrypted during operation, artifacts may remain recoverable.

Serverless ephemeral compute platforms provide compute ephemerality but not storage ephemerality; backing storage (e.g., S3, EBS) remains persistent.

In contrast, EFC uniquely enforces:
- Cryptographic key evolution with erasure
- Threshold-distributed fragments
- Task-scoped lifetime τ
- Automatic expiration of both key and fragments

This combination provides temporal bounding absent in existing architectures.

D. Threat Surface Comparison Metric
Define cumulative exposure risk over time T:
$R_{system}(T) \propto Exposure\_Window \times Data\_Persistence$
For persistent systems:
$R_{persistent}(T) \propto T$
For EFC:
$R_{EFC}(T) \propto \tau$
Since $\tau << T$ in typical use cases, exposure accumulation is significantly reduced.

This formalizes EFC's structural advantage beyond conventional encrypted storage models.

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