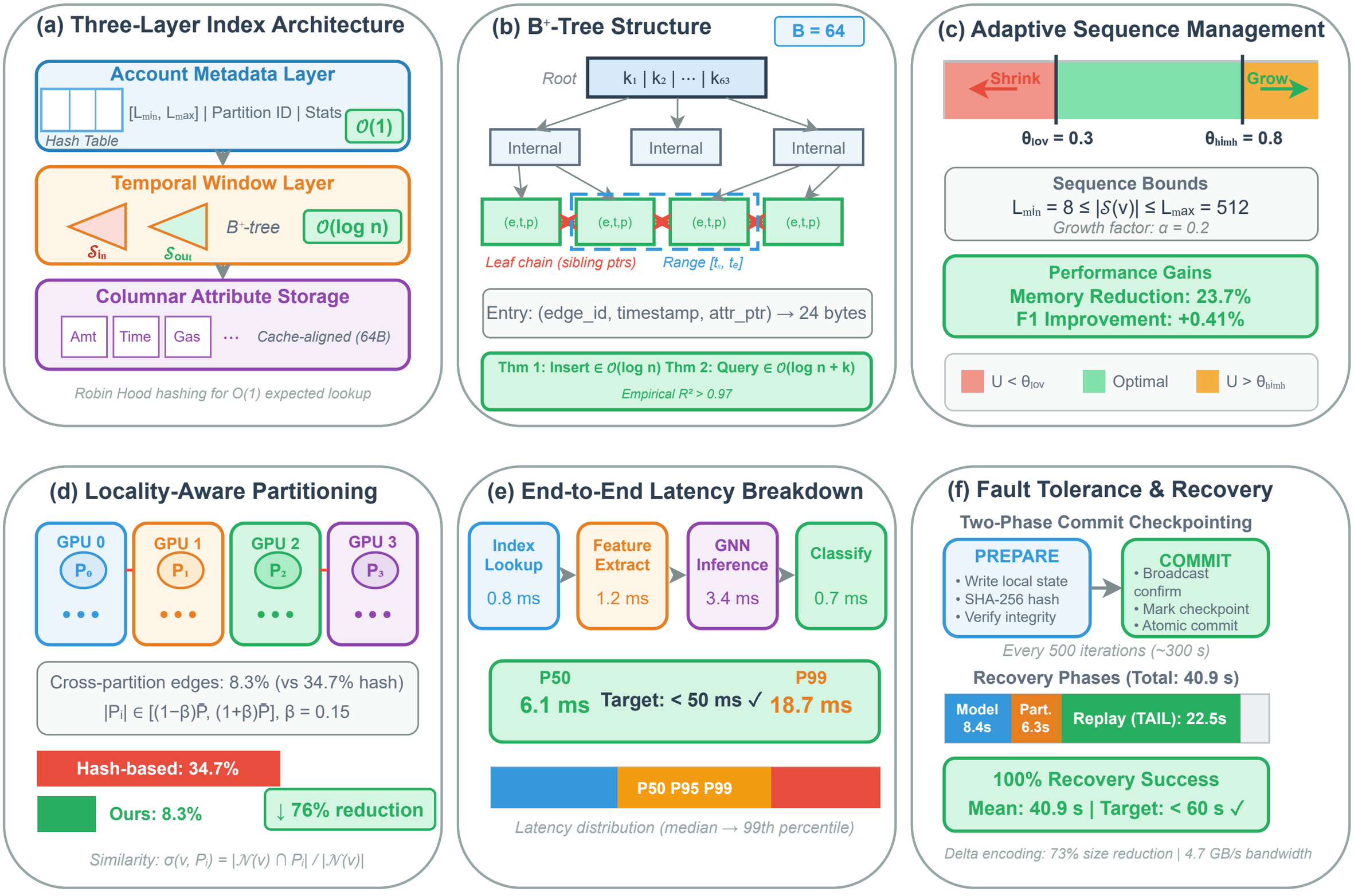
(a) Three-Layer Index Architecture
Account Metadata Layer
[Lmin, Lmax] | Partition ID | Stats
Hash Table
O(1)
Temporal Window Layer
B+-tree
O(log n)
Sin
Sout
Columnar Attribute Storage
Amt
Time
Gas
Cache-aligned (64B)
Robin Hood hashing for O(1) expected lookup
(b) B+-Tree Structure
B = 64
Root
k1 | k2 | ··· | k63
Internal
Internal
Internal
(e,t,p)
(e,t,p)
(e,t,p)
(e,t,p)
Leaf chain (sibling ptrs)
Range [ts, te]
Entry: (edge_id, timestamp, attr_ptr) → 24 bytes
Thm 1: Insert ∈ O(log n) Thm 2: Query ∈ O(log n + k)
Empirical R² > 0.97
(c) Adaptive Sequence Management
Shrink
Grow
θlov = 0.3
θhimh = 0.8
Sequence Bounds
Lmin = 8 ≤ |S(v)| ≤ Lmax = 512
Growth factor: α = 0.2
Performance Gains
Memory Reduction: 23.7%
F1 Improvement: +0.41%
U < θlov
Optimal
U > θhimh
(d) Locality-Aware Partitioning
GPU 0
P0
GPU 1
P1
GPU 2
P2
GPU 3
P3
Cross-partition edges: 8.3% (vs 34.7% hash)
|Pi| ∈ [(1−β)P̄, (1+β)P̄], β = 0.15
Hash-based: 34.7%
Ours: 8.3%
↓ 76% reduction
Similarity: σ(v, Pi) = |N(v) ∩ Pi| / |N(v)|
(e) End-to-End Latency Breakdown
Index Lookup
0.8 ms
Feature Extract
1.2 ms
GNN Inference
3.4 ms
Classify
0.7 ms
P50
6.1 ms
Target: < 50 ms ✓
P99
18.7 ms
P50 P95 P99
Latency distribution (median → 99th percentile)
(f) Fault Tolerance & Recovery
Two-Phase Commit Checkpointing
PREPARE
• Write local state
• SHA-256 hash
• Verify integrity
COMMIT
• Broadcast confirm
• Mark checkpoint
• Atomic commit
Every 500 iterations (~300 s)
Recovery Phases (Total: 40.9 s)
Model 8.4s
Part. 6.3s
Replay (TAIL): 22.5s
100% Recovery Success
Mean: 40.9 s | Target: < 60 s ✓
Delta encoding: 73% size reduction | 4.7 GB/s bandwidth