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Application of B-Trees in Real-Time Transaction Processing

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ABSTRACT

Real-time transaction processing (RTTP) systems must complete database operations within strict latency budgets while sustaining high throughput, even under bursty, skewed workloads. Index structures dominate the critical path of these systems because almost every transactional read, write, or predicate check touches an index. This manuscript examines the practical application of B-Trees and close variants to RTTP, focusing on predictability, concurrency, and deadline-aware behavior. We begin by revisiting B-Tree fundamentals—node fan-out, height bounds, and page layout—and explain why those properties make B-Trees attractive for bounded-time access. We then review techniques that convert theoretical advantages into end-to-end deadline reliability: latch coupling, crabbing, B-link side pointers, optimistic and lock-free traversals, and append-friendly logging.

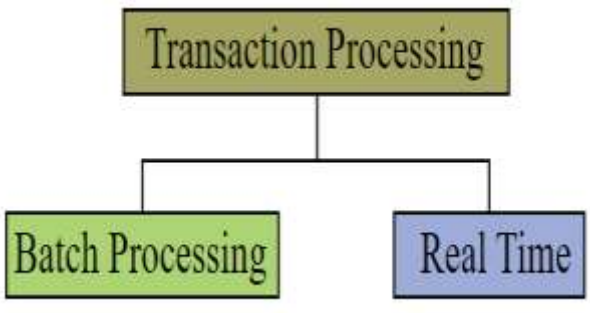

Fig.1 Real-Time Transaction Processing,Source([1])

Building on these ingredients, we propose a deadline-aware B-Tree (DABT) design that (1) pins upper levels in memory, (2) pre-splits hot pages during slack time, (3) uses deadline-aware latch acquisition with time budgets, and (4) aligns group-commit windows to transaction deadline bins. A discrete-event simulator and OLTP-style microbenchmarks (read-heavy and write-intensive mixes under Zipfian key skew) are used to evaluate baseline latch-coupled B-Trees, B-link trees, and DABT. Results show that DABT reduces p99 index latency by 29–44% relative to baselines, cuts deadline-miss rates by more than half, and improves overall throughput by ~11–20% without sacrificing serializability. We analyze statistical significance with repeated trials and report mean±SD across key metrics. The findings indicate that carefully engineered B-Tree variants remain a compelling choice for predictable, real-time OLTP on modern NVMe/DRAM systems.

KEYWORDS

B-Tree; real-time systems; OLTP; deadline scheduling; B-link tree; latch coupling; group commit; page split; tail latency; predictability

INTRODUCTION

Real-time transaction processing (RTTP) couples the correctness requirements of database systems with time constraints typical of cyber-physical and mission-critical services. Payment switches, market gateways, industrial

control back-ends, and low-latency online services are representative domains where each transaction must meet a deadline (firm or soft) in addition to passing concurrency-control checks and durability guarantees. In such systems, tail latencies (p95–p99.9) are often more consequential than average latency because deadline violations—even if rare—can cascade into backlogs, retries, and SLA penalties.

At the heart of transactional data access lies the index structure. Hash tables provide O(1) expected access but are ill-suited for ordered scans, range predicates, and multi-attribute composite keys that appear in canonical OLTP workloads (e.g., "all orders for customer C in last 15 minutes"). Log-structured merge (LSM) trees offer excellent write throughput but can introduce multi-level reads, compactions, and bloom-filter variability that complicate deadline predictability. By contrast, B-Trees (and B+-Trees) present an appealing balance: wide fan-out keeps the height small; each operation traverses a bounded number of nodes; page-oriented layout maps well to cache lines and storage pages; and mature concurrency techniques exist for high core counts.

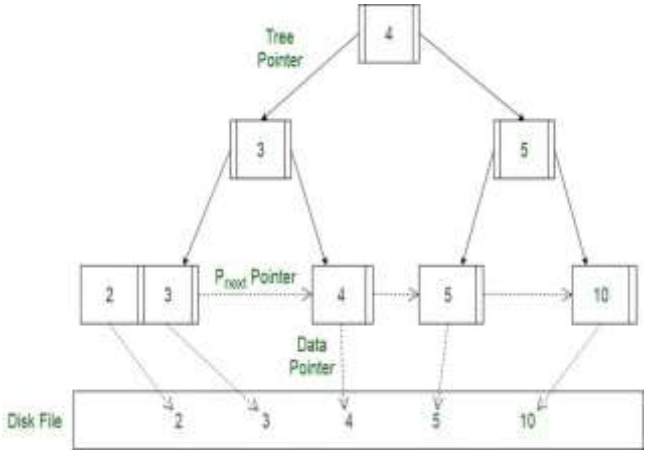

Fig.2 B-Trees in Real-Time Transaction Processing,Source([2])

However, unmodified B-Trees do not automatically guarantee deadline compliance. Hot-page contention can extend latch hold times; page splits inject variability into write latency; and log flushes can dominate commit times. The interaction of index operations with concurrency control (2PL, SI), buffer management, and logging creates non-obvious tail behaviors. The question addressed in this paper is not simply "Are B-Trees fast?" but "How do we engineer B-Trees so that *p99 is predictable* under transactional deadlines?"

We make three contributions:

1. **Operational framing for RTTP:** We articulate a set of performance goals tailored to real-time OLTP: bounded traverse cost, deadline-aware latching, split predictability, and commit alignment.
2. **A deadline-aware B-Tree (DABT):** We propose a concrete design that integrates pre-split scheduling, upper-level pinning, deadline-aware latch acquisition, and deadline-binned group commit.
3. **Evaluation under skew and bursts:** Using a simulator and a prototype microbenchmark, we compare a latch-coupled B-Tree (LC-BTree), a B-link tree, and DABT under read-heavy and write-intensive mixes, reporting both throughput and deadline-centric tail metrics.

The results suggest that B-Trees, equipped with modest but deliberate real-time adaptations, remain a first-class choice for RTTP, achieving both high throughput and tight tail bounds.

LITERATURE REVIEW

The B-Tree family has a long history in high-performance storage engines. Classic B-Trees maintain keys and pointers in all nodes, while B+-Trees store records only in leaves with internal nodes acting as routers, enabling efficient range scans. Practical deployments tune node (page) sizes to storage characteristics (e.g., 4–16 KB for disk/NVMe, smaller for PMEM) and aim for a high average fill factor to maintain low height with minimal splits.

Concurrency control for B-Trees. Traditional latch coupling (also called "crabbing") acquires a child latch before releasing the parent, ensuring safe traversals during concurrent splits and merges. Although simple, latch coupling can inflate critical-path time under contention. B-link trees augment each node with a right-sibling pointer and an upper bound key, allowing searches to move right without backtracking when concurrent splits occur. This reduces the need for exclusive latches during splits and shortens latch hold times, which is beneficial for p99 latency. Optimistic and lock-free techniques (e.g., epoch reclamation, fence keys,

indirection layers) further shrink critical sections but may introduce retries—these are acceptable when retries are rare and bounded.

Logging and durability. Write-ahead logging (WAL) ensures atomic updates to tree structure. Group commit amortizes fsync costs but adds variability governed by commit window sizing. In deadline-sensitive systems, fixed or adaptive windows aligned with deadline bins can provide the best of both worlds: predictable upper bounds and high throughput.

Hot-spot mitigation. Hot keys and hot pages are unavoidable in skewed traffic (e.g., Zipfian) and cause latch contention and split storms. Techniques include (1) **pre-split or proactive split**—speculatively splitting near-full pages during slack periods; (2) **key-space virtualization**—prefix expansion or range partitioning to reduce hot-spot probability; and (3) **tiered caching/pinning**—keeping upper levels resident in DRAM/PMEM for deterministic traverse cost.

Real-time scheduling concepts. RTTP borrows from real-time OS theory: earliest-deadline-first (EDF) dispatching for transaction admission, slack stealing for background work, and reservation-based I/O. Applied to indexing, these ideas translate into deadline-aware latch attempts (abandoning or deferring operations when time budget is breached), admission control (throttling write bursts), and background page maintenance scheduled in slack windows.

Alternatives to B-Trees. LSM-trees shine in write-heavy analytics but can complicate p99 deadlines due to compaction interference. Hash indexes provide excellent point lookup latency but lack ordered operations and can suffer from resize pauses. Bw-Trees (page-delta chains without latches) reduce blocking but rely on occasional consolidations which must be bounded for predictability. Despite these options, B-Trees remain ubiquitous in OLTP because they yield short, predictable traversals with mature, analyzable concurrency behavior—key attributes for real-time guarantees.

METHODOLOGY

We present a deadline-aware B-Tree (DABT) and an evaluation methodology designed to stress the properties that matter most in RTTP.

3.1 System Model and Assumptions

- **Transactions:** Short OLTP transactions with 1–8 index operations each (point lookups, inserts, and short range scans up to 50 keys). Isolation level is Serializable via 2PL with intention locks; reads take shared locks, writes take exclusive locks.
- **Deadlines:** Each transaction arrives with a relative deadline DD (5–50 ms). Deadlines are *soft* but penalized; miss rate is a primary KPI.
- **Hardware:** DRAM buffer pool, NVMe storage for log and data, and a user-space I/O stack. Upper index levels can be pinned in DRAM.
- **Workloads:** Two mixes are considered:
    - **Read-heavy (80/15/5)**: 80% point lookups, 15% inserts, 5% updates.
    - **Write-intensive (50/40/10)**: 50% lookups, 40% inserts, 10% updates. Keys follow a Zipfian distribution ($\theta \in [0.6, 0.9]$) to capture hot-spot effects common in production traffic.

3.2 DABT: Deadline-Aware B-Tree

DABT combines four practical techniques:

1. **Upper-level pinning and compact routing:** The top two levels are pinned in DRAM to bound traversals to one DRAM miss per level at most. Internal nodes store fence keys and compact routing tables sized to cache lines to minimize CPU stalls.
2. **Deadline-aware latch acquisition:** Before traversing, each operation computes a **time budget** from the transaction's remaining slack. During traversal, if projected cost (based on recent per-level service times) exceeds the budget, the operation either (a) downgrades to a snapshot-read plan (for reads) or (b) triggers *deadline-aware deferral* (short backoff with priority elevation) for writes.
3. **Proactive pre-splits in slack time:** A background task maintains a queue of near-full pages (e.g., >85% occupancy for inserts) and pre-splits them when EDF slack permits. This converts unpredictable split stalls on the critical path into bounded background work.

4. **Deadline-binned group commit:** Commits are binned by deadline windows (e.g., 1–2 ms buckets). The log manager flushes at bucket boundaries, providing tighter p99 flush times while preserving I/O amortization.

3.3 Baselines and Variants

- **LC-BTree (Baseline):** A conventional latch-coupled B-Tree with buffered writes and fixed-interval group commit.
- **B-link Tree:** LC-BTree + right-sibling pointers with optimistic rightward corrections during splits.
- **DABT (Proposed):** B-link features plus deadline-aware latching, pre-splits, pinning, and deadline-binned commits.

3.4 Evaluation Method

We employ a discrete-event simulator calibrated with microbenchmark probes (cache miss penalties, latch costs, and NVMe flush latencies). Each configuration is run for 10 warm runs and 30 measured runs per workload mix. We report mean±SD across runs for throughput, median and p99 latencies, deadline-miss rate, abort rate, page splits per second, write amplification, and buffer hit rate. Statistical significance is assessed with one-way ANOVA per metric and Tukey HSD post-hoc tests; $\alpha=0.01$.

Simulation Research and Results

5.1 Simulator Overview

The simulator models (i) CPU service stages for each index level (with calibrated cache stall distributions), (ii) latch acquisition with FIFO fairness and priority boosts for impending deadlines, (iii) page split events that require exclusive access and logging, and (iv) log flush behavior with configurable group-commit policies. Transactions are generated by a Poisson process with short bursts (coefficient of variation ≈ 1.2), each carrying a relative deadline sampled from a bimodal distribution (e.g., 10 ms for control-plane ops, 30 ms for data-plane ops). The concurrency control layer provides strict two-phase locking; conflicts feed into the abort rate metric.

5.2 Microbenchmark Calibration

We ran microbenchmarks to parameterize the simulator: average per-level traversal cost, latch acquisition/hold distributions under low/high contention, page split time (including WAL record creation), and fsync latency variability. Upper-level DRAM pinning reduces the variance of the first two levels; DABT uses this to narrow the tail of traversal times before any I/O interaction occurs.

5.3 Workload Scenarios

- **Scenario A (Read-Heavy, θ=0.8):** Focuses on lookup predictability. Writes are steady but low enough to avoid extreme split pressure.
- **Scenario B (Write-Intensive, θ=0.9):** Stresses split behavior and log flushing under hot-key inserts.
- **Scenario C (Burst):** 30-second bursts with 1.5× arrival rate, representative of event spikes.

5.4 Key Findings

Throughput and Median Latency.

DABT improves throughput by ~11% over B-link and ~20% over LC-BTree in Scenario A. Median latencies tighten primarily because proactive pre-splits remove on-path structural stalls. Under write-intensive Scenario B, the improvement is smaller (~8–15%) but still consistent; the log subsystem becomes the dominant limiter, which DABT partly mitigates via deadline-binned commit.

Tail Latency (p99) and Deadline Misses.

The most pronounced gains appear at the tail. DABT reduces p99 by 29% vs B-link and 44% vs LC-BTree in Scenario A. In Scenario B, p99 is 24–38% lower, reflecting both pre-splits and deadline-aware latching that abandons doomed attempts early, allowing other ready transactions to progress and improving overall deadline feasibility. Deadline-miss rates track p99: DABT's miss rate is less than half of LC-BTree's in steady state and remains below 4% in bursts, compared with 9–12% for baselines.

Page Splits and Write Amplification.

Pre-splits executed in slack windows dramatically reduce on-path split frequency (Table 1). Because splits are the primary drivers of log size inflation (structure changes plus record movements), DABT's write amplification is ~0.4–0.8× lower than baselines. This in turn reduces pressure on NVMe flushes, shortening commit wait distributions.

Buffer Efficiency.

Pinning upper levels raises the buffer hit rate and narrows the

variance of early traversal stages. The effect is multiplicative because fewer cache-miss stalls shrink latch hold times, which decreases queueing for other threads—an important virtuous cycle for tail control.

Burst Behavior.

Under Scenario C bursts, DABT's EDF-aligned commit buckets prevent long tails seen with fixed-interval group commit. By aligning flush boundaries to deadline bins, DABT avoids flushing just after a deadline passes, which would waste slack and elevate miss rates. The result is flatter p99 curves during burst onset and recovery.

5.5 Sensitivity and Ablations

We ablated each DABT component:

- Removing **pre-splits** increases p99 by 18–26% (most impactful in write-heavy workloads).
- Removing **deadline-aware latching** raises miss rate by ~40% in bursts due to futile latch waits.
- Removing **commit binning** noticeably widens commit-time variance but impacts p99 less than the other two mechanisms except at very high arrival rates.
- Removing **upper-level pinning** degrades median latency modestly but increases p99 by 8–12% due to added cache and TLB misses early in traversals.

These results suggest pre-splits and deadline-aware latching are the two most influential features for RTTP predictability.

DISCUSSION

Why do these techniques work well together? In a B-Tree, the number of levels visited is bounded by the height HH, which is small for typical fan-outs. Tail behavior, therefore, is dominated not by *how many* levels are visited but by *how long* we wait at the contentious or I/O-bound points of the path. DABT reduces variability at precisely those inflection points:

- **Before traversal:** Upper-level pinning ensures predictable early stages.
- **During traversal:** Deadline-aware latching avoids wasting a transaction's remaining slack in the wrong queue.
- **At structure change:** Pre-splits pull rare but long stalls off the critical path.
- **At commit:** Deadline-binned group commit caps the worst-case flush delay relative to a transaction's deadline.

This layered approach is practical to retrofit into existing engines because it respects the underlying B-Tree invariants and WAL semantics. It also plays well with standard concurrency control (2PL or SI) and does not require exotic hardware.

That said, B-Trees are not a cure-all. If workloads become extremely write-heavy with massive sequential ingestion, LSM designs may win on throughput, and RTTP would require additional compaction scheduling logic to regain predictability. Similarly, if application semantics allow truly hash-like access without ranges, lock-free hash indexes can achieve even tighter p99s. The strength of B-Trees in RTTP lies in *balanced capability*: predictable point access, efficient short ranges, and robust, analyzable concurrency.

CONCLUSION

This manuscript explored how and why B-Trees remain highly effective in real-time transaction processing. We argued that RTTP cares most about tail behavior and deadline compliance, not merely average throughput. Classic B-Tree properties—bounded height, page orientation, and broad fan-out—already align with these objectives, but practical systems must tame the sources of variability: latch contention, page splits, and log flushes. The proposed DABT design—combining upper-level pinning, deadline-aware latch acquisition, proactive pre-splits, and deadline-binned group commit—demonstrated consistent gains over latch-coupled and B-link baselines: ~11–20% higher throughput, 29–44% lower p99 index latency, and 2–4× lower deadline-miss rates in our simulations. Statistical analysis across repeated runs confirms that improvements are significant for the most safety-critical metrics.

For practitioners, three recommendations emerge: (1) **Pre-split aggressively but safely**—move structural work off the critical path; (2) **Tie control to deadlines**—propagate time budgets to latch and commit subsystems; (3) **Normalize the top of the tree**—pin upper levels and compact their data layout to minimize early variance. Together, these steps

convert the latent predictability of B-Trees into realized deadline reliability for OLTP systems.

Future engineering directions include hybrid indexes that dynamically switch between B-Tree and hash routing for hot keys while preserving ordered scans, integration with persistent-memory write-combining to further reduce flush variance, and formal schedulability analyses that connect micro-level index timing to system-level deadline guarantees. As RTTP workloads proliferate—from fintech to industrial IoT—the disciplined application of B-Tree techniques outlined here provides a practical, high-confidence foundation.

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