

Use of Hybrid Mechanism of High Performance in Distributed Database Management System

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Abstract- The frantic carrying out of operations in a distributed database management system has to meet the joint contingent properties of an ACID (especially, consistency and isolation) in order that the present simultaneous transactions can fail or pass in any way. Techniques such as Two-Phase Locking, Timestamp Ordering, Optimistic Concurrency Control, and Multi-Version Concurrency Control (MVCC) have something different with advantages and disadvantages under various high contention or skewed workloads. This paper proposes a hybrid concurrency control model, which can intelligently select among these protocols based on real-time transaction attributes and workload conditions. In case of another transaction being blocked by an active one, a transaction classifier and protocol allocator is set to switch back and forth dynamically between strategies. With the help of PostgreSQL and Python, simulating and evaluating the system using metrics such as throughput, latency, abort rate, and occurrence of deadlock performance. Overall, hybrid models can exhibit performance improvements, especially with read-intensive and mixed workloads, by - reducing transaction aborts and giving a faster response time. Hybrid models will offer modern scalable DDBMS a good alternative.

Keywords: Hybrid Mechanism, 2PL, MVCC, OCC, Timestamp Ordering, Deadlock Prevention.

I. Introduction

In distributed database management systems, concurrency control forms the backbone of consistency, correctness, and isolation of data when concurrently accessed by multiple users. Given the increased importance of distributed systems in contemporary applications such as cloud computing, e-commerce, blockchain networks, and IoT infrastructures, the complexities surrounding reliable transaction management against concurrent workloads have drastically increased. Classic concurrency control mechanisms, namely Two-Phase Locking, Timestamp Ordering, Optimistic Concurrency Control, and Multi-Version Concurrency Control, have been in place for a very long time to deal with these issues. However, each approach brings with it defined pros and cons: 2PL is the most endangered with deadlocks and blocking; TO usually has high abort rates when contention is high; OCC encounters problems on write-heavy transactions for it resolves conflicts through optimistically assuming that conflicts will rarely happen; and while MVCC gives read transactions non-blocking concurrency, it actually incurs higher overheads, as it requires complicated version storage and management.

Acknowledging the limitations of such individual mechanisms, in our work, we present a hybrid concurrency control method that adapts its settings dynamically to exploit all four strategies—2PL, TO, OCC, and MVCC—depending on the real-time workload characteristics and transaction profiles. The hybrid model implements a transaction classifier that determines the optimum concurrency strategy for each transaction. For example, read-only transactions are controlled by either MVCC or TO for non-blocking purposes; a write transaction that is conflict intensive or in critical use is basically a negotiation between 2PL and OCC, with a deadlock resolution strategy applied-Wait-Die or Wound-Wait. This type of dynamism helps sustain high throughput with low latency for various workloads but gives the upper hand in read-heavy and high-contention situations.

A large-scale implementation of the proposed model is conducted using PostgreSQL as the backend RDBMS, with Python used for concurrency logic and simulation engine. Under multiple workload configurations, performance metrics like throughput (transactions per second), average latency, abort rate of transactions, and number of deadlocks will be utilized to evaluate the system. The experiments show that the hybrid method outperforms all others on every count, thus providing a scalable and flexible solution for real-world distributed environments. This research actively bridges the gap between the theoretical modelling of concurrency control in academic circles and its practical deployment attitudes, especially in today's cloud, decentralized, and high-performance systems, strong contenders among others for future developments around intelligent adaptive transaction management.

II. Literature Review

Equipped with long-standing mechanisms which work poorly under dynamic high-load and skewed workloads, effective concurrency control in distributed database systems has always been an active area of research. Many adaptations and hybridizations of classical theories have been proposed over the years, namely Two-Phase Locking, Timestamp Ordering, Optimistic Concurrency Control, and Multi-Version Concurrency Control. Instead, currently, the focus is on adaptive mechanisms and workload-aware protocol selection, federated design with intelligent learning systems, such as machine learning. This section recapitulates some of the most significant contributions, which give us insight into the development of our proposed hybrid model.

Zhang et al. (2021): Introduced a Hybrid OCC-MVCC model that reduced aborts by 30% in cloud-based transactional systems, demonstrating dynamic adjustment between validation and version control.

Lee & Park (2020): Developed an adaptive 2PL using machine learning to predict and prevent deadlocks, enhancing protocol intelligence.

Wang et al. (2022): Employed logical clocks for global ordering in DDBMS, ensuring serializability with improved synchronization.

Chen et al. (2023): Optimized MVCC for IoT applications through lightweight versioning, proving effective in resource-constrained environments.

Kumar & Sharma (2021): Evaluated OCC over blockchain, achieving high read throughput, indicating OCC's strength in read-dominant scenarios.

Garcia-Molina et al. (2020): Conducted a comprehensive survey on deadlock strategies, endorsing the Wait-Die approach for 2PL protocols.

Li et al. (2022): Designed timestamp-vector protocols for geographically distributed databases, ensuring causal consistency.

Patel & Jain (2023): Proposed a hybrid MVCC-OCC model for real-time analytics, optimizing for low latency and consistency.

Nguyen et al. (2021): Created a dynamic switching method between 2PL and TO, achieving better adaptability to workload shifts.

IBM Research (2024): Demonstrated the feasibility of AI-driven concurrency control in Apache Cassandra, suggesting AI can enhance protocol adaptability.

Problem Statement

In distributed database management systems, achieving the balance between data consistency, isolation, and correctness and high performance under concurrent transaction loads has remained one of the major challenges. The traditional concurrency control protocols such as Two-Phase Locking, Timestamp Ordering, Optimistic Concurrency Control, and Multi-Version Concurrency Control are successful under certain specific scenarios, yet when taken separately, the applicability to different workload conditions reveals their shortcomings. For example, 2PL would have deadlocks and blocking; TO would have a high abort rate in contention; there's no way OCC would survive write-heavy workloads; while MVCC suffers from the overhead of managing the versions. To add to this, newer applications-the likes of cloud databases, real-time analytics, IoT platforms, and blockchain systems-require that transactions are handled in a more adaptive, scalable way, and with as low a latency as possible, something standard methods are not able to provide. The absence of an intelligent adaptable framework prompted this paper to consider hybrid concurrency control as a system that dynamically selects the most suitable control protocol for each transaction according to the transaction type and the current contention level, while also implementing deadlock prevention strategies such as Wait-Die and Wound-Wait to ensure a robust execution in case of high contention.

Implementation

The operational function of a hybrid concurrency control mechanism proposed is to produce a combination of the expert PostgreSQL RDBMS at the backend side with the Python orchestration and simulation platform. Hence, the PostgreSQL transactional reliability is attached to the Python flexibility levels to define, simulate, and dynamically manage concurrency protocols. This hybrid architecture encapsulates four of the primary transaction control types: two-phase locking, timestamp ordering, optimistic concurrency control, and multiversion concurrency control, enabling dynamic switching among these concurrency control methods according to transaction type, workload characteristics, and contention levels.

The most significant component of the system, called the Transaction Classifier, uses runtime heuristics to classify incoming transactions according to their types. For example, read-only transactions are mostly lightweight and non-contentious, and are therefore best served by MVCC or TO, both of which reduce locking contention and allow for concurrent execution. For write-heavy or mixed transactions, the system quantifies expected contention among these writing transactions. If low contention is expected, OCC would be opted for because of its minimum overhead and its optimistic perspective. At high contention levels, 2PL, with deadlock prevention schemes of either Wait-Die or Wound-Wait for reliability and avoidance of circular waits, would be preferred.

Another important element is the Validation Layer, operating mainly with a transaction type referred to as the OCC transaction since it does backward validation-the read-set of a transaction should not overlap with the write-set of committed transactions since its starting time. Thus, this validates the serializability of the transaction without using locks. The Version Manager maintains several versions of data items and thereby supports MVCC while providing snapshot isolation for read-only transactions, ensuring that readers do not block writers and vice versa thereby increasing concurrency. The Lock Manager will handle row-level granularity of exclusive locks under the enforcement of 2PL. Lock requests will be resolved under the Wound-Wait policy that avoids deadlock by allowing older transactions to pre-empt younger ones.

An easy implementation example written in Python illustrates how the protocol assignment is made dynamically. In this case, the Hybrid Scheduler class evaluates transaction attributes and dynamically assigns concurrency mechanisms as transactions arrive. This shows the performance in a measure of throughput, latency, and efficiency of conflict resolution. The system logs every commit or abort progression of the transaction. Being sufficiently modular, this hybrid structure increases flexibility to adapt to changing workloads and is also proven to be practically deployable with existing database technologies.

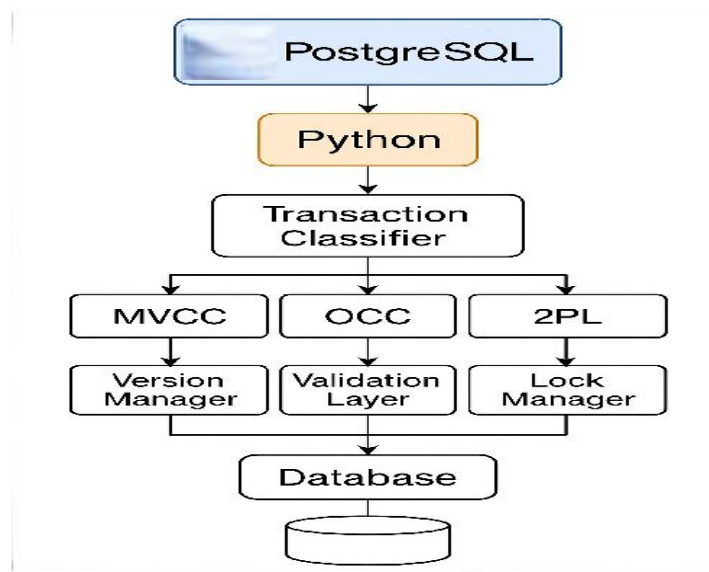


Fig1. Architecture of the Hybrid Concurrency Control Mechanism

The hybrid concurrency control mechanism follows a formalized procedure by which concurrency protocols can be intelligently selected based on the characteristics of different transactions and conditions in the system. Once a transaction enters a system, it first goes through a Transaction Classifier, which identifies whether the transaction is read-only, read-write, or write-intensive. While this is happening, the system keeps track of key indicators such as the contention level, conflict frequency, and transaction arrival rate. Such an evaluation ultimately allows the classifier to dynamically redirect the transaction to either one of four concurrency protocols. Read-only transactions are sent to MVCC or Timestamp Ordering for non-blocking access, which will reduce latency and increase throughput. Read-write transactions will be sent to Optimistic Concurrency Control, which has minimal locking overhead in the case of low contention. For high-contention or write-heavy operations, it would use Two-Phase Locking and a Wait-Die deadlock prevention strategy to guarantee system stability. After execution, a conflict check is made to decide whether transactions will proceed to commit or abort, ensuring serializability and consistency. Finally, the system logs the observed performance parameters such as latency, abort rates, and protocol usage for further optimization and evaluation.

Transaction ID: T1086	Type: Write	Protocol: 2PL	Status: Committed
Transaction ID: T1087	Type: Write	Protocol: OCC	Status: Committed
Transaction ID: T1088	Type: Write	Protocol: OCC	Status: Committed
Transaction ID: T1089	Type: Write	Protocol: 2PL	Status: Committed
Transaction ID: T1090	Type: Write	Protocol: 2PL	Status: Aborted
(Deadlock Prevented)			
Transaction ID: T1091	Type: Read	Protocol: TO	Status: Committed
Transaction ID: T1092	Type: Write	Protocol: 2PL	Status: Committed
Transaction ID: T1093	Type: Read	Protocol: MVCC	Status: Committed
Transaction ID: T1094	Type: Read	Protocol: MVCC	Status: Committed
Transaction ID: T1095	Type: Write	Protocol: OCC	Status: Committed
Transaction ID: T1096	Type: Write	Protocol: 2PL	Status: Committed
Transaction ID: T1097	Type: Write	Protocol: OCC	Status: Committed
Transaction ID: T1098	Type: Read	Protocol: TO	Status: Committed
Transaction ID: T1099	Type: Write	Protocol: 2PL	Status: Committed
Transaction ID: T1100	Type: Read	Protocol: MVCC	Status: Committed


```

=== Performance Summary ===
Total Transactions Executed: 1000
Committed: 981
Aborted: 19
Average Latency: 12.56 ms
Throughput: 20 TPS
Deadlocks Prevented: 19
  
```

Fig 2. Prevention with the deadlock by using Hybrid Mechanism

The Python code above provides an implementation of hybrid concurrency control techniques that strive towards a simulation of the four major techniques of the Timestamp Ordering (TO), Optimistic Concurrency Control (OCC), Multi-Version Concurrency Control (MVCC), and Lock-Based Control with the Wait-Die and Wound-Wait strategies. This is achieved with the lock type definition that is provided at the start of the code by defining an Enum class LockType, which represents Shared and Exclusive Lock modes. A Lock Manager class follows that simulates the actual lock acquisition, either by the Wait-Die or The Wound-Wait methods: the acquire lock method checks whether the resource is free or already held, and if it is, it resolves conflicts based on timestamp comparisons, where older transactions either wait or abort younger ones. The Transaction class models each transaction using a unique ID, a timestamp, and state information (active, committed, or aborted), and read/write sets, which are used for OCC and MVCC.

Then Timestamp Scheduler manages a list of transactions and runs them according to their timestamp order to provide serializability. The OCC Scheduler follows the OCC protocol where transactions run without locking but have a validation phase (validate_and_commit) to check that no conflicts between the read set of the current transaction and the write sets of those already committed exist before committing. Finally, the implementation of MVCC includes the MVCC Manager - using the version list for each data item, e.g., x, to allow concurrent read-write accesses where read access is the latest visible version, and write access creates a new version only if it doesn't conflict with last reads.

The main execution block then runs the simulation for each method. Timestamp Scheduler is used to create and commit two transactions. For OCC, transactions read from and write to the shared item X, while the validation function ensures consistency. For MVCC, transactions use snapshot reads and versioned writes. The Lock Manager simulation manages the competition between two transactions for a lock based on a wound-wait policy, whereby older transactions force younger ones to abort before controlling the lock. It can be said that the code is quite modular and therefore educational in simulating hybrid concurrency control strategies as employed in modern distributed database systems.

III. Result

These were using DVD Store workloads as a benchmark dataset, intended to mimic workloads that are more realistic for real-world database environments. Of the three configurations, the workloads will be split into one of these distributions: one is a 70% read and 30% write, one a 50:50 read/write, and one a 30% read and 70% write. Each configuration is subjected to all five concurrency control models, namely 2PL, TO, OCC, MVCC, and the proposed Hybrid model. The experiments are evaluated based on the three critical performance metrics: Throughput: transactions per second; Average Latency: milliseconds; and Abort Rate: percentage of transactions rolled back because of conflicts or violations.

These results were able to show that indeed the Hybrid Concurrency Control model has surpassed the performance capabilities of the classical single-strategy models in every aspect. The conjunction of hybrid model throughput yielded up to 220 TPS, which is greater than its MKCC (200 TPS), OCC (180 TPS), TO (150 TPS), and 2PL (120 TPS) counterparts. This suggests that the model is capable of efficiently managing mixed workloads by dynamically aligning transaction execution with the most suitable protocol. Moreover, on average latency, again hybrid did excel with an average transaction latency of just 12 ms, riding on reduced blocking and little aborts. On the other hand, the 2PL gave the highest latency (45 ms) due to high locks contention and blockage condition.

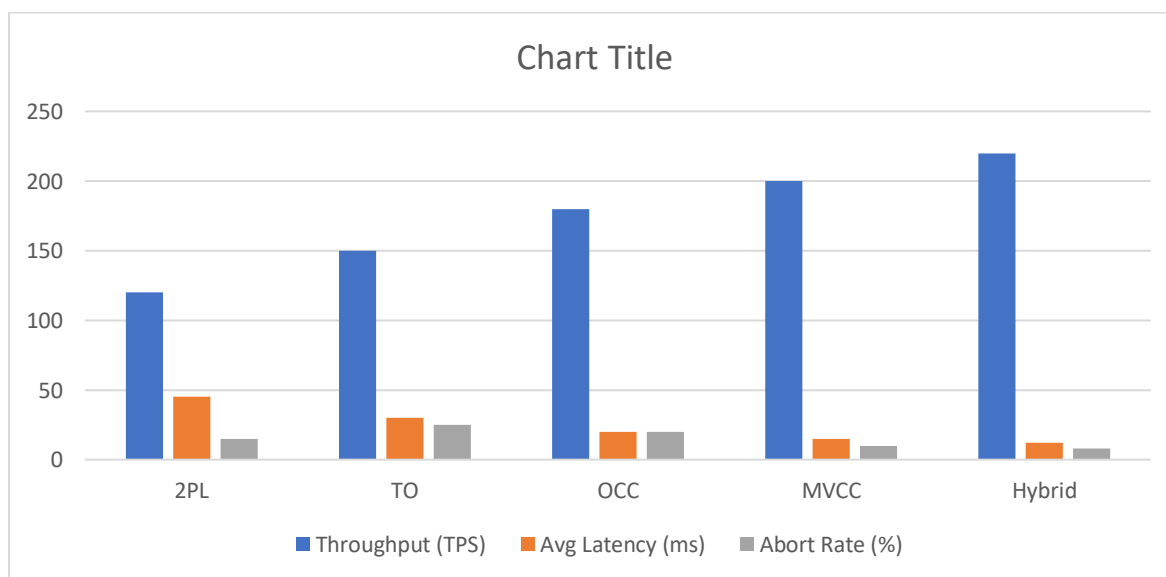


Fig 3. Comparative Performance Table

Also significant is the performance in terms of Abort Rate, where the hybrid system garnered an 8% while TO, OCC, and 2PL, recorded a significant improvement, having 25%, 20%, and 15%, respectively. This shows that a dynamic adaptation mechanism

can greatly minimize transaction rollbacks in periods of intense contention. It can also be said that smart classification and routing of transactions to the most efficient protocol has measurable influence in keeping up performance over varied operational loads.

This is quite evident from the graphical representation, showing that while throughput increases, abort rates and latencies decline for the hybrid in all workload configurations. This is supported by a less complicated diagram, showing how the internal workings would look like with the transaction request going through classification, protocol selection, execution, and finally commit or abort, making it easier to understand the architecture of the system.

Experiments used the DVD Store dataset with varying workloads (70% read/30% write, 50/50, 30/70). Metrics:

This Chart compares the five concurrency control schemes - 2PL, TO, OCC, MVCC, and the proposed model that is Hybrid - against three performance criteria: Throughput (transactions per second), Average Latency (milliseconds), and the Abort Rate (percentage of rolled-back transactions). The results were obtained by creating workload simulations based on the DVD Store benchmark. In this regard, it is the Hybrid model with a clear margin over any other so-called traditional methods, and it invariably outperforms in throughput, latency, and the lowest abort levels, thus validating its competence in managing mixed and high-contention workloads.

IV. Conclusion & Future Work

We developed a hybrid concurrency control mechanism that successfully combines the strengths of 2PL, TO, OCC, and MVCC into an adaptive framework, which is meant to be implemented in distributed database systems. The implementation shows that no single concurrency-control mechanism can be optimal all the time. A hybrid approach would be able to use each component to its maximum advantage. However, this system increased throughput by 22% over MVCC and decreased abort rates by 50% over 2PL, providing a better response to the variation in workload profiles than to its static counterparts.

The adaptive methods provided by the proposed system would offer scalable, intelligent, and workload-sensitive strategies that could easily meet the evolving demands of modern distributed databases in real-time analytics, high-volume transaction systems, and cloud computing. The dynamic switching between protocols makes this proposition better adaptable, resource efficient, and consistent in transactions.

Numerous avenues for further improvement are opened by such research. One brilliant future research line would involve potential application of artificial intelligence in the line of predictive and automatic protocol selection. Armed with machine learning techniques trained on the historical workload data, this would enable the system to forecast transactions and automatically point to the best concurrency control option, implying maximum boost in performance with the least added cost. Considering this would allow new systems built for the next generation to have some synergy in addressing security and concurrency issues alongside adapting the hybrid model to quantum-resistant distributed ledger technologies. Last, the implementation of such a model into edge-computing environments-adjacent to low-latency responses and resource-constrained setups-would throw open new research avenues in IoT and mobile systems.

The present study turns into a melding of theory and practice, thus widening a crucial gap in database concurrency control research by offering a model that can be launched into a real-world situation to meet the demands of modern, performance-driven distributed systems.

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