The Impact of Timestamp Granularity in Optimistic Concurrency Control

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Abstract

Optimistic concurrency control (OCC) can exploit the strengths of parallel hardware to provide excellent performance for uncontended transactions, and is popular in high-performance in-memory databases and transactional systems. But at high contention levels, OCC is susceptible to frequent aborts, leading to wasted work and degraded performance. Contention managers, mixed optimistic/pessimistic concurrency control algorithms, and novel optimistic-inspired concurrency control algorithms, such as TicToc [21], aim to address this problem, but these mechanisms introduce sometimes-high overheads of their own. We show that in real-world benchmarks, traditional OCC can outperform these alternative mechanisms by simply adding fine-grained version timestamps (using different timestamps for disjoint components of each record). With fine-grained timestamps, OCC gets 1.14× TicToc’s throughput in TPC-C at 128 cores (previous work reported TicToc having 1.8× higher throughput than OCC at 80 hyperthreads). Our study shows that timestamp granularity has a greater impact than previously thought on the performance of transaction processing systems, and should not be overlooked in the push for faster concurrency control schemes.

1. Introduction

Software running on shared-memory multi-core machines can perform and scale excellently if it uses machine resources well [1]. An important design principle is to avoid extensive sharing of frequently-written cache lines, which causes expensive locking at the underlying cache coherence protocol level. Optimistic concurrency control (OCC) [11] obeys this principle. It avoids writing memory for objects that are merely read, thus limiting the instances of read/write conflicts to those that are absolutely essential for the correct operation of the concurrency control (CC) mechanism. As a result, OCC is central to many recent very fast transaction processing systems [5, 10, 18].

However, OCC is susceptible to aborts under contention. Most OCC mechanisms perform read-set validation at the very end of a transaction. Any conflict discovered there will cause the entire transaction to abort and restart, causing wasted work. This is particularly a problem for long-running read-heavy transactions [9].

A number of systems have been proposed to address OCC’s performance issues under high contention. For example, contention managers can prioritize the execution of certain transactions over others to ensure better forward progress [4, 7]. Mixed or adaptive concurrency control can dynamically decide to use pessimistic techniques, such as two-phase locking, on frequently-written data [13, 16]. And OCC-based algorithms have been proposed that can commit strictly more transactions than conventional OCC. For example, TicToc can commit transactions that OCC would normally abort, without violating serializability, by tracking two timestamps per data item (a “most recently read” timestamp is added to conventional OCC’s “most recently written” timestamp) [21]. The papers introducing these ideas have shown significantly reduced aborts and better performance than OCC under high contention benchmarks.

We set out to replicate these results to validate the effectiveness of the proposed optimizations. We implemented one variant for each of the three classes of OCC-improving mechanisms mentioned above: SwissTM’s contention manager [4], a mixed concurrency control scheme based on our own adaptive reader-writer lock design, and TicToc. We implement all these systems and conduct our experiments on top of STO [8]. We were expecting to see these new mechanisms outperform the default OCC-based transaction engine in STO for high-contention workloads.

But that is not what we saw. Careful scrutiny of both the CC mechanisms in question and the workload itself led to this observation: in one of the most widely-used benchmarks, TPC-C [17], coarse-grained timestamps are largely to blame for OCC’s poor performance at high contention. By using fine-grained timestamps assigned to multi-column values, OCC outperforms all three OCC-improving mechanisms mentioned above. By reporting our findings, we show that the granularity of a CC mechanism is a crucial performance parameter not to be overlooked in the context of modern in-memory database systems.

2. Related Work

TDSL, the Transactional Data Structure Library [15], and STO, Software Transactional Objects [8], are STM frameworks integrated with libraries of transaction-aware data types. By testing conflicts at a higher level than previous word-based STMs [3], these systems can reduce the overheads associated with large transaction tracking sets and the frequency of false conflicts. When
used as an in-memory database, STO can outperform previous purpose-built database systems [18]. TDSL evaluates STM benchmarks, but offers support for extremely efficient single-operation transactions. We implement our in-memory database using STO, and extend STO to support multiple concurrency control mechanisms.

Contention managers [7] are enhancements to OCC addressing the issue of aborts under high contention. Instead of simply aborting and re-executing upon observing a conflict, the transactional system consults the contention manager to decide which transaction to abort. The contention manager makes the decision by assigning different priorities to different transactions, with the goal of ensuring the forward progress of the overall system. SwissTM [4] is an example of an STM system that has a contention manager built in. It promises $1.16 \times$ speed-up over TL2 [3] and can achieve comparable performance to more advanced type-based TM systems. We implement our own version of the SwissTM contention manager on top of STO and examine how it performs under a database workload.

There has been recent interest in systems that use mixed modes of concurrency control. Adaptive Concurrency Control (ACC) [16] is a system that dynamically switches between pessimistic and optimistic CC based on a pre-defined set of workload features like conflict rate, read/write ratio, etc. The system works in a partitioned fashion, where each CC mechanism operates exclusively in one partition, and the system ships data between partitions to select the appropriate CC mechanism for each record. The resulting mechanism is shown to outperform OCC under contended workloads. We implement our own adaptive CC mechanism based on a reader-writer lock. To lower the overhead of the mechanism, we do not use a partitioned approach, but create a unified commit protocol instead that handles different CC policies executed in the same transaction. We use a state machine per record to regulate the CC mechanism in use. Our approach is more lightweight compared to many other adaptive mechanisms and therefore better suits single-node in-memory database systems.

TicToc [21] attempts to improve OCC from within. It uses separate read and write timestamps for each record, allowing for more flexible transaction schedule reconciliation at commit time. TicToc is shown to allow serializable transaction schedules not possible under OCC or 2-phase locking. For example, consider the transaction interleaving in Figure 1, where 2 transactions access a table concurrently. TicToc can commit both transactions in this scenario, but OCC or locking-based mechanisms would have to abort at least one transaction. TicToc achieves this by rescheduling Txn 1 to commit before Txn 2 in the serialization order, despite Txn 1 finishing after Txn 2 in

| Txn 1 | Txn 2 |
|-------|-------|
| read row A | update row A |
| update row B | commit |

Figure 1: Example of a transaction interleaving where TicToc can commit both transactions but OCC can not.

A potential issue with TicToc is read timestamp maintenance: atomic compare-and-swap operations may be issued to shared metadata of objects that are merely read during the transaction. This appears to undermine a major performance argument of OCC. We examine this further by implementing our own version of TicToc.

Early work on database management systems showed that locking granularity impacts performance [14]. This suggested that finer granularity doesn’t always lead to better performance, but having some level of fine-grained locks is still better than having just one coarse-grained global lock. Despite its age, the study’s conclusion appears to hold even today. For example, SwissTM finds that 4 STM words per lock achieves better performance than 1 word per lock [4], and coarse-grained locking can outperform fine-grained locking in some Java-based benchmarks by as much as $3 \times$ [6].

Much work on synchronization granularity concerns pessimistic locking, rather than the OCC-based synchronization widely used in modern in-memory database systems. Our work shows that fine-grained timestamps in OCC can be a clear win in real-world benchmarks, largely because of OCC’s low overhead per timestamp. We show that the gains achieved by using fine-grained timestamps in OCC are greater than those achieved by using the aforementioned alternative CC mechanisms.

3. Implementation

This section is an overview of the software platform we use to obtain our results.

3.1. STO

We build an in-memory database in STO by constructing a special datatype for database indexes and tables. The datatype we implemented is based on Masstree [12], a cache-friendly concurrent B-tree data structure. We extended Masstree under the STO framework to support transactional insert, select, update, scan, and delete operations.

3.2. Flexible Concurrency Control

We extended STO to support other CC schemes, specifically Adaptive Read/Write Locking, 2-Phase Locking, SwissTM Concurrency Control, and TicToc.
Adaptive Read-Write Locking This mechanism uses an adaptive reader-writer lock guarding access to each record. The reader-writer lock automatically switches between optimistic mode (where reads don’t acquire locks but only observe versions, like in OCC) and pessimistic mode (where a strict reader-writer lock is enforced) based on the level of contention observed with the associated record.

2-Phase Locking This is just the simple 2-Phase Locking mechanism where a lock has to be acquired before accessing a record. We use reader-writer locks.

SwissTM Concurrency Control In this mechanism, we use SwissTM’s combination of an eager locking (for writes) OCC with a timestamp-based contention manager. The contention manager favors the longer-running transaction based on the timestamps, and aborts the other transaction.

TicToc We implemented TicToc as described in Yu et al. [21], modified according to their published implementation [19]. Yu et al. describe several optimizations to the basic protocol. One of these, non-waiting deadlock prevention (§5.1 of [21]), is enabled by default in STO for all CC. Another, compressed 64-bit timestamps (§3.6), performed far worse than a simpler 128-bit implementation because version number overflow caused TicToc to abort more than OCC. We found that preemptive aborts (§5.2) did not improve performance.

We designed and implemented a unified commit protocol providing simultaneous support for these CC mechanisms within the same transaction. This approach is correct as it only allows the intersection of the permitted schedules of participating CC mechanisms. The unified commit protocol implements OCC no slower than the original OCC-only protocol.

3.3. Benchmarks

We evaluate these CC mechanisms using standard benchmarks, specifically YCSB [2] and TPC-C [17].

Our YCSB-like workload uses the YCSB key-value schema, but groups several operations into transactions. The YCSB table is prepopulated with 10 million keys before the benchmark starts, each associated with a value that consists of 10 columns (10 bytes per column). Each transaction comprises 16 operations, ~50% reads and ~50% writes, which randomly selects a key and randomly reads or writes one of its associated columns. To simulate a high-contention workload, transactions access keys according to a Zipfian distribution with θ = 0.9 over all keys in the database.

TPC-C is a widely-used industry standard evaluating the performance of transaction processing systems. It models a moderately-complex transactional inventory management application. We implement the New-order, Payment, and Order-status transactions of TPC-C, which account for 92% of all transactions in the TPC-C default workload mix. The contention level of TPC-C can be controlled by varying the number of “warehouses”; fewer warehouses per core means more contention.

As is typical, we associate each value (i.e., each 10-column YCSB value and each TPC-C row) with a single timestamp. Any change to a value updates the timestamp, invalidating any concurrently-reading transactions.

3.4. Timestamp Granularity

TicToc claims to outperform OCC on TPC-C and other benchmarks by reordering transactions, as shown in Figure 1. We analyzed the TPC-C benchmark to understand where this reordering occurred. Due to space constraints we describe only the instance involving District tables:

- A New-order transaction in TPC-C reads a row from a District table to access the district tax rate information. This is a read-only operation.
- Concurrent Payment transactions may update the district year-to-date amount (YTD) field in the same District table row, overwriting the row that’s read by a New-order transaction.
- New-order and Payment transactions subsequently write to completely different tables.

In this case the New-order transaction acts like Txn 1 and the Payment transaction acts like Txn 2 in Figure 1.

Note, though, that New-order and Payment transactions operate on disjoint fields of the same row. If the field updated by Payment had a different timestamp than the rest of the row, OCC would see no conflict at all. The conflict it does detect is actually false.

TicToc’s multi-part timestamp manages to partially mitigate this false conflict based on other properties of the transaction (namely the relative orders of writes and reads within each transaction), but it is also possible to address the false conflict directly. We implement fine-grained timestamps in TPC-C by associating each District and Customer row with two timestamps, one guarding the rarely updated fields of the row (e.g. tax rate for District tables) and another guarding the rest. In YCSB, we implement one timestamp for even-numbered columns and one for odd-numbered columns. Locking mechanisms use fine-grained locks rather than timestamps.

Our main evaluation questions are whether fine-grained timestamps have significant overhead, and if not, whether they allow conventional OCC to perform on par with other CC schemes.

4. Experiments

In this section, we describe our experimental setup and results of the TPC-C and YCSB benchmarks.
4.1. Experimental Setup

We run our experiments on a machine with 8 Intel Xeon E7-8990 v4 CPUs @ 2.20 GHz. The system has a total of 192 physical cores and 512 GB of RAM. Each experiment runs for a fixed time duration of 15 seconds, and we report the median of 7 consecutive runs, with maxes and mins shown as error bars.

4.2. YCSB-like Workload

The YCSB-inspired synthetic microbenchmark evaluates these CC systems under high-contention stress. (At lower contention levels, as expected, all mechanisms perform well.) Results of the experiments are shown in Figure 2. Because the performance trend closely tracks that described in Yu et al. [21], and because our implementation of TicToc outperforms in absolute terms the TicToc implementation reported in its paper, we believe we have TicToc implemented fairly.\(^1\)

\(^1\)After 64 threads, the absolute performance of our implementation is slightly below that in Yu et al. We believe this is because our machine has twice the number of sockets and a more complex topology than theirs.

Figure 2a shows the results of the benchmark when we use a coarse-grained timestamp for each value. As the number of threads increases, increasing conflict rates lead to performance degradation for all CC mechanisms. TicToc starts off better than OCC due to its ability to reschedule transactions and avoid aborts, but ends up much worse than all other CC mechanisms as parallelism increases. The overhead of extending TicToc read timestamps via compare-and-swap, especially under a high contention workload, is pronounced on this many-core machine, leading to more aborts. The other mechanisms (SwissTM, Adaptive, and 2PL) perform uniformly worse than OCC. These mechanisms were designed to provide benefits for specific transaction mixes; for example, SwissTM ensures forward progress for long-running transactions. But many mixes are not favorable, and unfavorable mixes instead highlight the mechanisms’ overheads.

Figure 2b uses finer-grained timestamps/locks, which reduce, but do not eliminate, conflicts. All CC mecha-
nisms benefit from increased timestamp granularity in this benchmark, with OCC and SwissTM observing the most gains compared to coarse-grained timestamps.

4.3. TPC-C Workload

The TPC-C workload is a more realistic transaction-processing workload than YCSB. To model high contention, our TPC-C configuration fixes the number of warehouses at 8, so conflicts will occur due to concurrent accesses to the same warehouse as the core count increases.

Figure 3a shows TPC-C results with coarse-grained timestamps. As in previous work, TicToc achieves gains over other CC mechanisms as contention increases, up to 96 threads (data point not shown). At 64 threads, TicToc achieves an abort rate of only 9.79%, significantly lower than that of the closest performing system in terms of aborts, OCC, which reports an abort rate of 17.57%. TicToc’s performance begins to degrade at 128 threads, losing to 2 Phase Locking. This performance drop at high core counts is consistent with the results shown in the TicToc paper, and the trend is also observed, as expected, with all other optimistic mechanisms (OCC and SwissTM). The absolute performance difference between TicToc and OCC is less than the maximum 1.8 × previously reported, however, due most likely to STO’s baseline OCC implementation being more efficient than that on TicToc’s measurement platform, DBx1000 [19, 20] (e.g., STO defaults to non-waiting deadlock prevention).

Figure 3b introduces fine-grained timestamps/locks on District/Customer tables, allowing all mechanisms to avoid false conflicts. Unlike with coarse-grained timestamps, OCC is now the fastest mechanism at almost all measured core counts (Adaptive has a slight advantage at 32 cores). Switching to fine-grained timestamps reduces OCC’s abort rate at 128 threads from a whopping 30.91% to 1.75%, the largest drop observed in all systems. It appears that, at least on TPC-C, TicToc’s benefits are due to false conflict avoidance, not true conflict rescheduling. Similar to YCSB, all mechanisms increase in throughput. TicToc never out-performs OCC but still manages to gain ground over locking-based mechanisms, showing that fine-grained timestamps improve the performance of optimistic mechanisms more than pessimistic ones.

In these experiments we do not observe any slowdowns due to increased timestamp granularity. The benefits of avoiding false conflicts in this benchmark greatly outweigh the overhead incurred by maintaining more timestamps per record. Furthermore, these results demonstrate that TicToc and other mechanisms’ performance benefits at high core counts in Figure 3a are also achievable by using OCC with fine-grained timestamps.

In fact, OCC with fine-grained timestamps outperforms TicToc with coarse-grained timestamps by 1.37 × at 96 threads, where TicToc’s performance peaked. When we use fine-grained timestamps for all systems, OCC still outperforms TicToc by as much as 1.14 × at 128 threads.

5. Future Work

Our results open up doors to further investigations of the impact of timestamp granularity on CC mechanisms. We would like to investigate whether this result applies to additional real-world workloads. TicToc can reschedule transactions with true conflicts; perhaps other real-world workloads offer examples of important reschedulable true conflicts, although we have found none yet. We would be interested in designing a CC scheme that can automatically detect false conflicts due to coarse-grained timestamps and address them by dynamically increasing timestamp granularity. We also plan to perform similar evaluations on distributed CC mechanisms to test our findings in a distributed setting.

6. Conclusion

Aborts in OCC under high contention is a focus of research in in-memory concurrency control, and various CC mechanisms are proposed to address this issue. In this work, we set out to verify the claims made by various OCC improvements. We implement and measure the performance of a variety of CC mechanisms using both synthetic and real-world high contention workloads. We demonstrate that timestamp granularity plays a significant role in the performance of all CC mechanisms. In particular, the improvements to OCC by the alternative CC mechanisms we implemented are also achievable by baseline OCC when fine-grained timestamps are used, and OCC out-performs all other CC mechanisms when fine-grained timestamps are in use at high core counts. Our findings demonstrate that timestamp granularity has a greater impact on the performance of CC mechanisms than previously thought, and it has been somewhat overlooked during recent quest for faster or more complicated CC mechanisms. We plan to extend our evaluation to more workloads in the future to further solidify our claim that timestamp granularity should be treated as a complementary avenue to addressing OCC’s abort issue at high contention.

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