Partial Replication for Software Transactional Memory Systems

(extended abstract of the MSc dissertation)

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***Abstract*—Nowadays, transactional in-memory distributed storage systems are widely used as a mean to increase the performance of applications that need to access frequently large amount of shared data. In this context, data replication has two main advantages: it supports load balancing and fault-tolerance. However, these advantages need to be weighted against the costs of replications: namely memory consumption and coordination costs. This motivates the use of partial replication. In order to maximize performance and scalability, these platforms typically rely on weakly consistent partial replication mechanisms, sacrificing consistency and ensuring guarantees that are weaker than classic *1-Copy Serializability*.**

This thesis addresses the problem of supporting partial replication in transactional in-memory distributed storage systems. Although solutions have been proposed for partial replication in database management systems, there are significant differences between the two type of systems. Namely, transactional in-memory distributed storage systems avoid many of the costs involved in the management of database transactions, which amplifies the costs of replica maintenance. Therefore, the thesis aims at assessing the efficiency of partial replication in the context of transactional in-memory distributed storage systems.

The thesis presents the following contributions: proposes a set of algorithms to support partial replication in transactional in-memory distributed storage systems; and presents an experimental evaluation of these algorithms using a prototype implementation that has been integrated in *Infinispan*. In opposition to the algorithms used in the current *Infinispan* implementation, based on Two-Phase Commit, our algorithms avoid deadlock scenarios. Our performance evaluation highlights speed-ups when using the proposed algorithms with respect to the native *Infinispan* replication mechanism.

***Keywords*-Partial Replication, Distributed Memory, Transactional Memory, Atomic Multicast**

I. Introduction

Nowadays, transactional in-memory distributed storage systems are increasingly used to improve the performance of applications that require frequent access to large amounts of data, by decoupling the persistent memory access from the critical path of the application. YouTube, Wikipedia, Twitter and Facebook are a few examples of applications that make use of this architectural approach. The key reason underlying the success of these platforms lies in their ability to achieve higher performance, scalability and elasticity, when compared to classical SQL-based database management systems. This is achieved thanks to the reliance on (i) simpler data models, e.g., key/value pairs vs. relational model, (ii) more efficient application interfaces, namely embedded vs. JDBC/ODBC connections, and (iii) the reliance on in-memory replication and asynchronous write to disk vs. (per-transaction) synchronous logging to disk.

In this context, data distribution and replication has two main advantages: it allows distributing load among multiple replicas, enhancing throughput; and it ensures the survival of data if a replica fails. This last point is particularly relevant, since the data is first stored in volatile memory and made persistent asynchronously (and would therefore be lost in case of failure, if it was not replicated).

However, there are also costs inherent to replication that must not be overlooked. Firstly, replicas consume memory, reducing the amount of data that can be stored. Also, the larger the number of replicas, the more expensive it becomes to ensure their consistency. This motivates the use of partial replication.

Partial replication tries to overcome these disadvantages by configuring the storage system in such a way that each item is replicated in a subset of nodes and no node stores all the data. This thesis studies the use of partial replication techniques in the context of transactional in-memory distributed storage systems. Even though partial replication has already been applied to distributed databases [1], there are significant differences in the workloads imposed to both systems related to the execution of transactions [2] (see the examples described before). So, several of the platforms have opted for relaxing consistency, ensuring weaker semantics than the classical *1-Copy Seriliazability* [3] in order to allow more efficient implementations.

In this thesis we present set of replication algorithms. The algorithms ensure weak consistency criteria, but they rely on the usage of total order primitives [4] to ensure agreement on the transaction serialization order. We start by developing the algorithm for full replication using the *Total Order Broadcast* (TOB) primitive, and later evolves it for a partial replication context. In partial replication, the algorithm relies on the usage of a *Total Order Multicast* (TOM) primitive, to ensure agreement on the transaction serialization order in a genuine fashion [5] i.e. involving in the coordination for a transaction T only the nodes responsible for storing a copy of the data accessed by T. Thanks to their reliance on total order primitives, the proposed protocols avoid the occurrence of distributed deadlocks, which represent the key source of inefficiency in Two-Phase Commit (2PC) based replication schemes [6].

We integrated the proposed algorithms into one of the mainstream open-source storage platforms, namely Red Hat's/JBoss' *Infinispan*. *Infinispan* is a weakly consistent transactional in-memory distributed storage systems that represents the reference solution to support clustering of the well-known JBoss AS (probably the most widely used Java application server at the time of writing [7]).

We perform an experimental evaluation study in which we compare the performance of the proposed total order based schemes with those built-in into *Infinispan*, which rely on a classical 2PC-based replication scheme. We consider both synthetic workloads, which allow to assess the protocol performance in heterogeneous (and clearly identifiable) scenarios, and industry standard benchmarks for OLTP systems, namely the TPC-C benchmark [8]. Our experimental study highlights that the proposed total order based schemes achieve striking speed-ups with respect to classic 2PC-based solutions in high contention scenarios, while achieving very similar performance in presence of workloads with very limited contention.

The rest of this document is organized as follows. Section II compares our solution with related work. Section III briefly describes *Infinispan* and how it manages replication and distribution. Section IV presents the mechanisms of partial replication developed to enhance *Infinispan*. In Section V the performance of the proposed system is evaluated. Finally, Section VI concludes this thesis.

II. Related Work

This work results from the confluence of three different but closely related lines of investigation, namely: transactional in-memory distributed storage systems, database replication techniques, and distributed software transactional memory systems.

Transactional in-memory distributed storage systems have emerged as tools to increase the performance of applications that require frequent low latency access to large amounts of data. The first proposed systems did not support transactions [18], [19], but more recent approaches have incorporated them in their architectures. *Sinfonia* [20] provides support for transactions and replication, but assumes that transactions are static, i.e., their read and write sets are known *a priori*. *TxCache* [21] relies on a back-end database to handle update transactions and ensures that read-only transactions users observe a strongly consistent snapshot of the cache (namely a consistent view of the system as of a specific timestamp). Conversely, our solution is designed to ensure weaker consistency criteria (repeatable-read with write-skew check being the strictest supported consistency criterion) and does not rely on any external transactional store to serialize update transactions.

The area of database replication is very rich in algorithms that ensure replica consistency in transactional environments. While most of these systems use full replication [22], [23], our focus is on those supporting partial replication [1], [24], [25]. *P-Store* [5] is probably the solution that is closer in spirit to the approaches proposed in this thesis. Also *P-Store* relies on a genuine algorithm, i.e., only the replicas involved in a given transaction participate in the coordination phase that ultimately leads to its commit or abort, and is built on top of a totally ordered multicast primitive. However, since *P-Store*'s algorithm provides stronger consistency guarantees, it also incurs in additional costs (e.g. always requiring the certification of read-only transactions accessing data hosted by remote replicas, the dissemination of the whole transaction read-set during the commit phase, and a voting phase to determine the outcome of update transactions spanning multiple replica groups) when compared to the solutions proposed in this thesis, which exploit a set of optimizations that are possible precisely because we target more relaxed consistency models.

Finally, distributed software transactional memory systems [2] appeared as an extension to software transactional memory systems [26] developed for multi-core machines. The vast majority either does not consider fault-tolerance [27], [28], or are fully replicated [29], [30], [31].

III. Infinispan

Infinispan [9] externalizes a simple key/value store interface, providing support for transactions and for two main operational modes: partial vs. full data replication (referred to as *distribution* and *replication*), depending on whether the data is replicated on a subset or on the whole set of nodes.

In the partial replication mode, *Infinispan* relies on a lightweight consistent hashing scheme [11] to partition data across replicas, ensuring good load balancing (in terms of number of keys hosted by each replica) and minimum reshuffling of keys in presence of joins/departures of nodes from the platform. Also, it supports replication of each key across a fixed, user-tunable number of replicas, achieving fault-tolerance without hampering scalability (unlike full replication schemes).

Infinispan supports transactions in a weak-consistent flavour, opting for more relaxed criteria than the classic *1-Copy Serializability* [3]. Specifically, *Infinispan* supports the following (weaker) consistency criteria [12]:

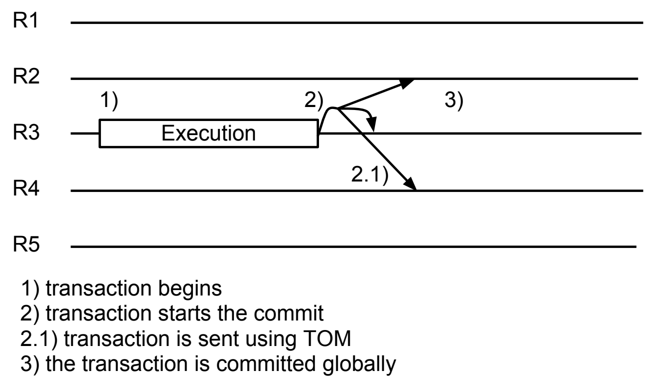
- *Read Committed (RC)* which ensures that a transaction can only read previously committed values;
- *Repeatable Read (RR)* which ensures that no two consecutive reads within the same transaction can return different values;
- *Repeatable Read with Write Skew Check (RR+WS)* which ensures the same as RR, it checks also if the value of a key was changed between a consecutive read and write operation of a transaction (aborting, in such a case, the transaction).

More in detail, for what concerns read operations, if the RC consistency criterion is being used, *Infinispan* simply returns the latest committed value. If, instead, RR is being used, whenever a transaction issues a read on a data item, it stores the returned value into its transactional context, and returns it in subsequent read operations. It is important to point out that the data is distributed, so read operations may require contacting other nodes (even though *Infinispan* tries to reduce the frequency of remote read operations by adopting an additional, so called, L1 cache [9]).

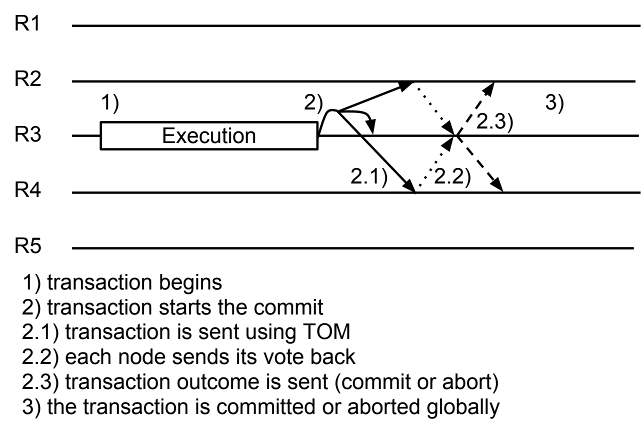
Write operations, on the other hand, do not require distributed interaction during transaction execution. Instead, whenever a key/value pair is updated/inserted/deleted (simply referred to as write operation in the following), the lock on the corresponding key is acquired locally during the transaction execution phase. If the write skew check is enabled (namely, the RR+WS consistency criteria are being used), however, a further check is performed upon issuing of a write operation: if the transaction had previously read that key, and its value is found to be different after having acquired the corresponding lock, the transaction is simply aborted.

Infinispan uses a classic Two-Phase Commit [13] (2PC) to ensure atomic updates in all replicas. During the first phase of 2PC, the nodes attempt to remotely acquire the locks on all the replicas that are responsible for storing the keys updated during the local execution of the transaction.

If the lock acquisition phase succeeds on all the contacted replicas, the transaction originator finally sends a commit message and commits locally. In presence of conflicting, concurrent transactions, however, the lock acquisition phase may fail due to the occurrence of distributed deadlocks. In *Infinispan*, deadlocks are detected using a simple timeout based approach and is coupled with an eager deadlock detection algorithm that detects circular, direct lock waits between two transactions (thus not detecting deadlocks due to chains of more than two transactions in circular transitive wait); *Infinispan* resolves the deadlock deterministically by aborting one of the blocked transactions. If the lock acquisition fails during the prepare phase, a negative vote is sent to the coordinator, which, in turn, instructs all replicas to abort the transaction.



(a) Algorithm for RC and RR



(b) Algorithm for RR+WS

Figure 1: Algorithms developed for the weaker consistency criteria

IV. TOM-based Partial Replication

Due to lack of space, we will only describe the solution for partial replication. However, the solution for full replication has the main idea. The main difference is on the total order primitive used, where in full replication is used a Total Order Broadcast primitive. As will you see, in partial replication is used a Total Order Multicast primitive.

As described in the previous section, *Infinispan* has already a built-in support for partial replication. Unfortunately, the 2PC-based replication scheme used by *Infinispan* is known to be prone to thrashing at non-minimal contention levels [6] due to the occurrence of distributed deadlocks.

In this section we present two Total Order Multicast [4] (TOM) based partial replication algorithms. These algorithms ensure the same weak consistency criteria currently supported by *Infinispan*, but, not incurring in distributed deadlocks, they can sustain much higher throughputs (committed transactions per second) especially in scenarios of moderate/high contention.

In the following, we first introduce the two TOM-based replication algorithms, and then discuss two alternative implementations of the TOM primitive, exhibiting a trade-off between the number communication steps and message complexity.

A. TOM-based Partial Replication Schemes

Both the partial replication algorithms presented in this thesis rely on the same base principle: using TOM to achieve agreement among all replicas whose keys have been updated by a committing transaction T on T's serialization order.

As in *Infinispan*'s baseline algorithm, in fact, transactions execute locally (with the exception of remote read operations, which may require to fetch data from remote nodes) until they enter their commit phase. At this stage, the entries updated by transactions (along with their previous read values, in case of RR+WS consistency) are sent, using TOM, to all the replicas that need to be updated. This set of replicas is given by the union of the replicas maintaining a copy of each of the keys modified by the transaction and is, typically, only a subset of the number of replicas that compose the system.

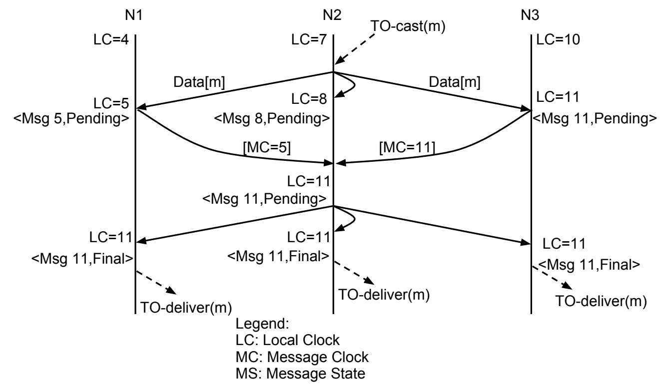
By relying on a TOM primitive to disseminate the above messages, we can guarantee that if two replicas deliver two updates, they do it in the exact same order. Therefore, if the consistency criteria is either RC or RR (see Figure 1a), the replicas can immediately apply the updates in the order in which they are delivered by the TOM primitive. This is sufficient to guarantee that all replicas apply the updates generated by all conflicting transactions in the same order, and is achieved in our implementation by having a single dedicated thread, which is awakened whenever a transaction is TOM-delivered, and is in charge of performing the write-back phase of both local and remote transactions.

On the other hand, if the consistency criterion in use is RR+WS (see Figure 1b), upon TOM-deliver of a transaction, replicas need to perform the write skew check in order to determine the transaction's outcome. This implies the need for the replicas to undergo an extra voting phase, during which each replica performs the write skew (on the keys of which is responsible) and sends back the result to the replica that executed the transaction. Before sending the final commit/abort message, the replica that executed the transaction needs to wait until it is informed of the successful outcome of the write skew check of all the updated keys. Note that, since all the replicas that are responsible for the same set of keys certify the transaction deterministically and in the same order, it is guaranteed that they all determine the same outcome for the transaction. Therefore, in order to commit a transaction, the transaction coordinator does not need to wait for positive replies from all the nodes that it had contacted via the TOM primitive, but only until it receives a positive vote for each updated key from *at least* one of the nodes over which the key is replicated. As in classic 2PC, instead, the transaction is aborted as soon a negative vote message is received.

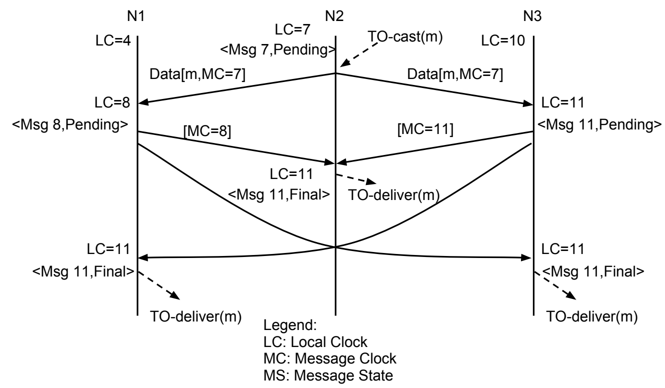
B. Implementing Total Order Multicast

We now address the implementation of the TOM primitive [4] used in the algorithms above. Informally, the TOM primitive allows disseminating a message m to a subgroup of the system replicas, denoted as $m.dst$, while ensuring agreement on the (total) order of delivery of messages in presence of i) concurrent TOMs triggered by different senders, ii) possible overlaps among the recipient sites of two TOMs, and iii) crashes of (a subset of) sites.

Formally, the TOM primitive guarantees the following properties: (i) *uniform integrity*: for any site s and any message m, s delivers m at most once, and only if $s \in m.dst$; (ii) *validity*: if a correct site s issues a TOM for a message m, then eventually all correct sites in $m.dst$ delivers m; (iii) *uniform agreement*: if site s delivers a message m, then eventually all correct sites in $m.dst$ deliver m; (iv) *uniform prefix order*: for any two messages m and m', and any two sites s and s', such that $\{s, s'\} \subseteq m.dest \cap m'.dest$, if s delivers m and s' delivers m', then either s delivers m' before m or s' delivers m before m'; (v) *uniform acyclic order*: the relation $<$ is acyclic, where $<$ is defined as follows: $m' < m$ if and only if any process delivers m and m' in that order.



(a) 3 phases



(b) 2 phases

Figure 2: Total Order Multicast Algorithms

We developed a TOM protocol for *JGroups*, inspired by the Skeen's algorithm described in [15] and used in an early version of the ISIS toolkit [4], which operates as follows (see Figure 2a). Each machine has a logical clock that is incremented when DATA or ORDER messages are received. The ordered multicast starts when a DATA message is sent to the group of replicas that participate in the transaction. When this message is received, each replica increments its logical clock, assigns the resulting timestamp to the message, changes the message's state to *Pending* and puts it in an ordered queue; the local order number is then sent to the replica that originally sent the message. The sender collects all the sequence numbers assigned by the other replicas, determines their maximum value, and sends it back to all replicas in an ORDER message. Upon receiving this ORDER message, each replica updates the order number of the corresponding message, changing the order in the queue if necessary, marks the message as *Final* and updates its own logical clock. Finally, messages are delivered to the application when its state is marked as *Final* and they are in the head of the queue (i.e., there are no messages marked as *Pending* or *Final* with a lower timestamp).

We have also developed another version of the total order multicast protocol in order to understand the trade off of having less communication steps but exchanging more messages in each round. Its mode of operation is very similar to the first version, except that, upon delivery of the DATA message, replicas send the ORDER message (which piggybacks their logical clock value) to *all* the replicas to which the message is being multicast. With this decentralized approach, a replica can mark a message as *Final*, as soon as it receives all the ORDER messages corresponding to a given DATA message.

This version requires one less communication step to complete the commit of a transaction, see Figure 2b. However, the number of point-to-point messages exchanged between replicas increases quadratically with the number of participating replicas. The next section compares the two approaches, identifying the strengths and weaknesses of each one.

V. EVALUATION

This section presents the experimental evaluation of the proposed algorithms implementing partial replication in transactional in-memory distributed storage systems context. This evaluation is based on a prototype developed by extending the code of *Infinispan* and *JGroups* to implement the algorithms described above.

A. Experimental Settings

All tests were ran on a cluster with 10 machines, where each machine is equipped with two 2.13 GHz *Quad-Core Intel(R) Xeon(R) E5506* processors and 16 GB of RAM, running *Linux 2.6.32-33-server* and interconnected via a private Gigabit Ethernet. We integrated the proposed TOM-based replication solutions in *Infinispan 5.0* and *JGroups 2.12*.

In our experiments, we use a number of machines varying between 4 and 10, and three distinct configurations of *Infinispan*: the native protocol and the TOM-based protocol with both TOM primitives. The timers to acquire locks expires after 10 seconds, and it uses the deadlock detection technique described in Section III. In both configurations we run experiments with replication degree of 2 and 4, which means that each key is stored in two or four replicas, respectively.

We used two different benchmarks to evaluate the system, *Radargun*, a benchmark created by RedHat specifically for this type of caches, namely *Infinispan*, EhCache [16] and Oracle Coherence [17]; and TPC-C [8], a more complex and realistic benchmark.

The workload used with *Radargun* tests was the following. The application executes as many transactions as possible for a period of 5 minutes, using 8 threads in each machine submitting concurrent transactions to the system. Each transactions is composed of 10 operations. On average, 10% of these operations are writes and there is always at least one write operation per transaction. This way, there are no read-only transactions in the workload, because they do not require replica synchronization. To simulate low contention scenarios, transactions access random objects from a set of 100.000 keys and to simulate high contention scenarios, transactions access random objects from a set of only 1.000 keys.

TPC-C is a benchmark that simulates a population of terminal operators executing transactions against a transactional data store. Transactions include entering new orders, querying the status of existing orders and entering payments from customers. The configuration we used is the following: one warehouse, 45% of payment transactions, 5% of query transactions (which means there will be 95% read-write transactions and only 5% of read only transactions) and 8 threads executing transactions on each machine.

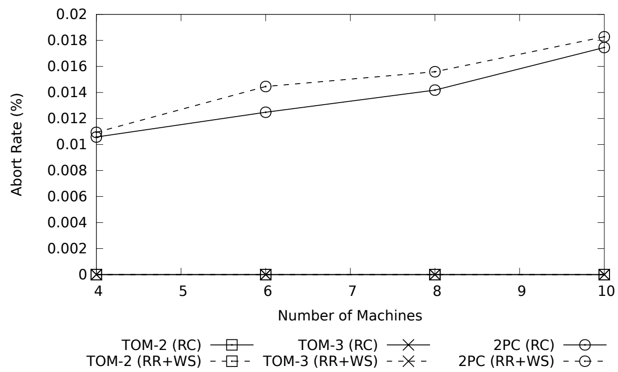
B. Results

In the following we present a comparative evaluation of *Infinispan*'s native solution (labelled as "2PC") and the two versions of our TOM implementation (labelled as "TOM-2" and "TOM-3" for the 2 and 3 communication step variants of total order multicast, respectively) using two consistency models: RC and RR+WS (the latter with write skew anomaly detection enabled). The three performance metrics used in the plots are: abort rate, throughput of the system (committed transactions), and commit latency (time to complete the commit phase).

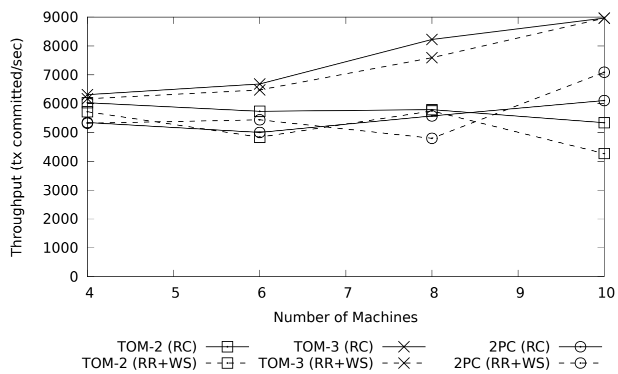
1) Abort Rate: Figures 3a and 5a depict the abort rate of the three algorithms in low and high contention scenarios for both consistency models and a replication degree 2 for *Radargun*. As expected, for the TOM algorithms, the abort rate is virtually non-existent, even for the RR+WS model. On the other hand, the native algorithm needs to acquire locks in every participating replicas, causing deadlocks (and consequently transaction aborts) in case locks are acquired in different orders at different replicas. This issue becomes more noticeable as we increase the number of nodes in the system and, finally, in high contention scenarios, where the abort rate peaks at 3% for a system with 10 nodes.

Figure 7a depicts the abort rate for TPC-C with a replication degree 2. This benchmark induces a very high contention on a small subset of data items. Specifically, each write transaction must update one out of 10 existing instances of the, so called, *District* entity. Let us analyze first the Read Committed isolation level scenario. In this scenario, 2PC suffers from an abort rate ranging from 30% to 45%, which is entirely due to the occurrence of deadlocks. On the other hand, with the same isolation level, the TOM-based solutions do not suffer from any aborts.

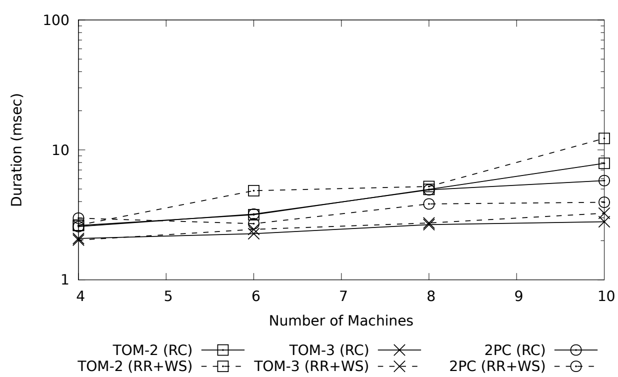
When considering the Repeatable Read isolation level with write skew detection, we observe that the 2PC and the TOM-based solutions incurs on a very similar abort rate, ranging from 40% to 70%. This depends on the fact that TPC-C is very likely to generate read-write conflicts which, in turn, cause the failure of the write-skew check. Note that failure of the write-skew check represents the only abort cause for the TOM-based solutions. With 2PC, instead, only 27% of the transaction aborts are imputable to write-skew check failures, with (distributed) deadlocks being by far the most common cause of aborts.



(a) Abort Rate

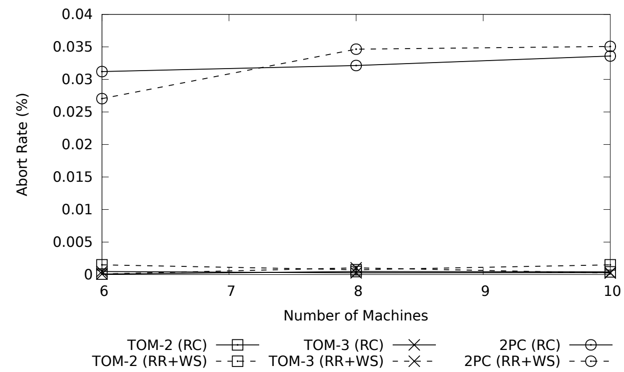


(b) Throughput

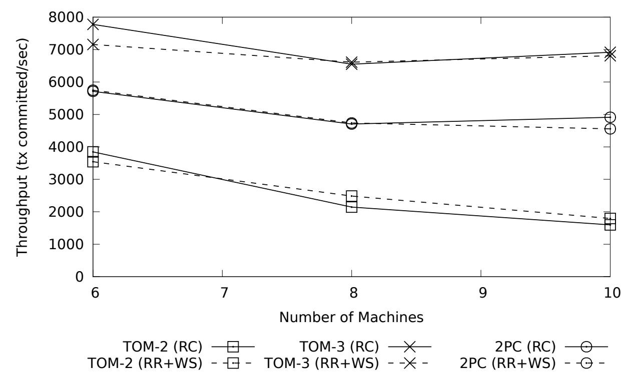


(c) Average Latency

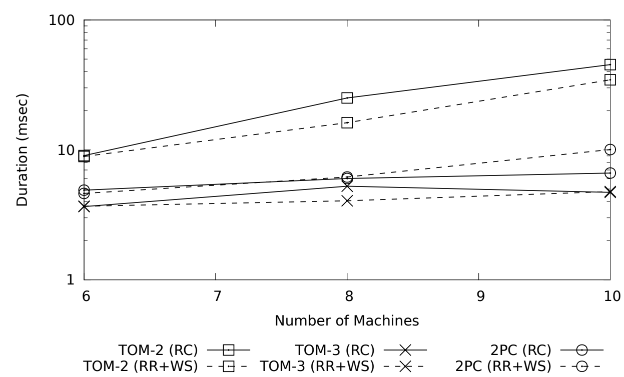
Figure 3: *Radargun*: Low Contention (Replication Degree 2)



(a) Abort Rate



(b) Throughput

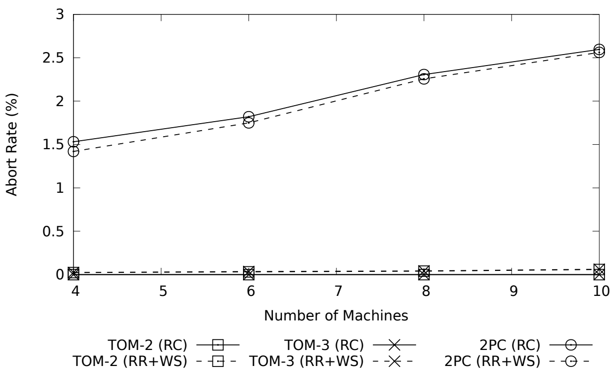


(c) Average Latency

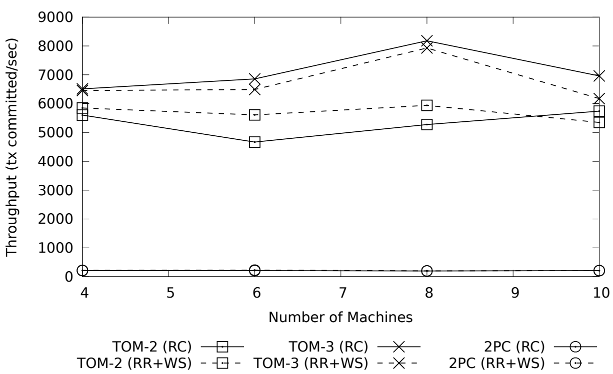
Figure 4: *Radargun*: Low Contention (Replication Degree 4)

Figures 4a and 6a depict the abort rate with a replication degree 4 for *Radargun*. Also in this scenario, analogously to the case of replication degree 2, the abort rate of TOM-based solutions is extremely low. Conversely, it is interesting to notice that, when increasing the replication degree from two to four, the abort rate grows of a factor close to 2 with 2PC. This is explicable because the number of replicas involved in the 2PC doubles, when using replication degree 4. Therefore, the probability of deadlocks also increases accordingly.

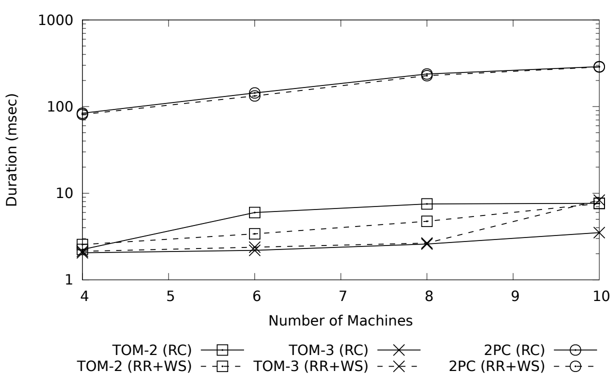
Figure 8a depicts the abort rate for TPC-C with a replication degree 4. The plots show an interesting trend: with 2PC, when increasing the replication degree from 2 to 4, the abort rate suffers of a significant increase. This is particularly true for the RC consistency level, where the abort rate grows from around 35%, with replication degree 2, to around 65%, with replication degree 4. Again, this is imputable to the fact that the chances of deadlocks are higher when more replicas are involved in the 2PC. On the



(a) Abort Rate

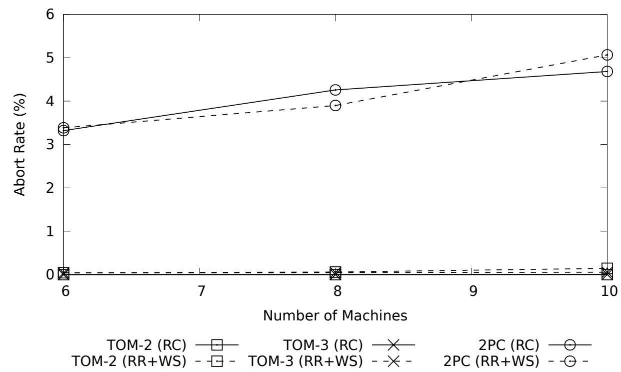


(b) Throughput

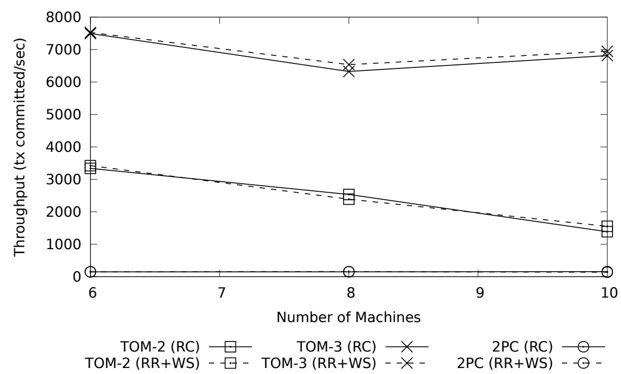


(c) Average Latency

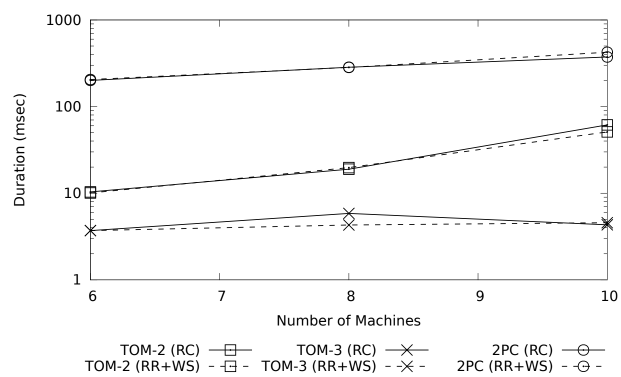
Figure 5: *Radargun*: High Contention (Replication Degree 2)



(a) Abort Rate



(b) Throughput

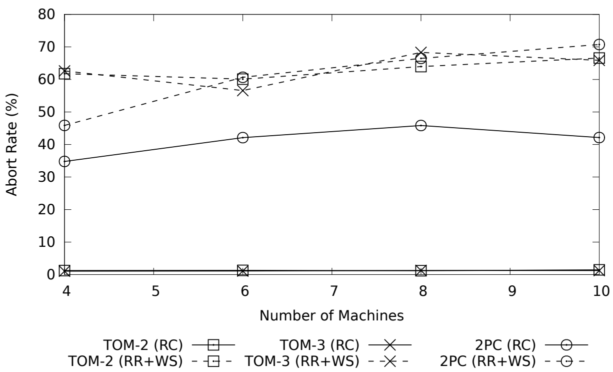


(c) Average Latency

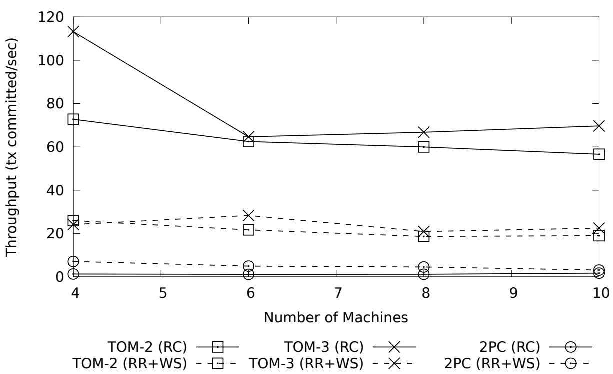
Figure 6: *Radargun*: High Contention (Replication Degree 4)

other hand, the increase of the replication degree from 2 to 4 has a negligible impact in the case of the TOM-based solutions (thanks to their deadlock freedom property). In other words, this means that TOM-based solutions, unlike 2PC-based schemes, allow achieving a higher degree of failure resiliency without determining increases of the abort rate (that as we will see in the next section have detrimental effect on performance).

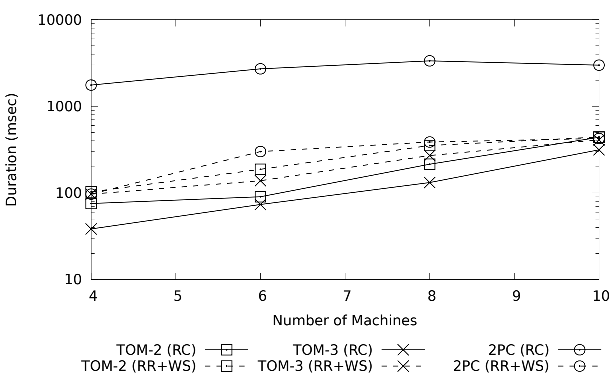
2) Throughput: Figures 3b and 5b present the effects of the abort rate on the throughput of the system using the *Radargun* benchmark with replication degree 2, measured as the number of committed transactions per second. In low contention scenarios, which is the most favourable scenario for the 2PC protocol, 2PC and TOM-2 have a similar throughput. However, TOM-3 has the best throughput. This is explainable by the fact that TOM-3 and 2PC have very similar communication patterns, but, unlike 2PC, TOM-3 does not incur in any deadlocks. The lower throughput for the TOM-2 is due to the high number of messages,



(a) Abort Rate

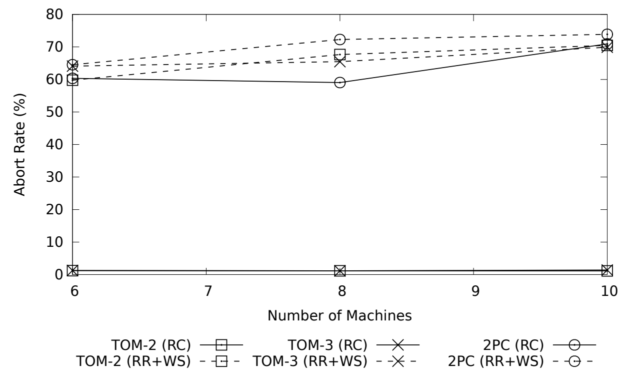


(b) Throughput

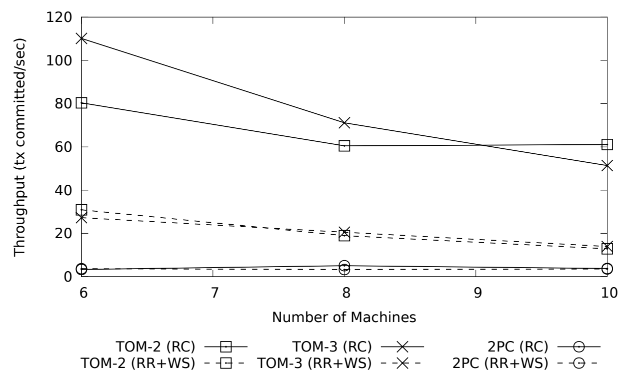


(c) Average Latency

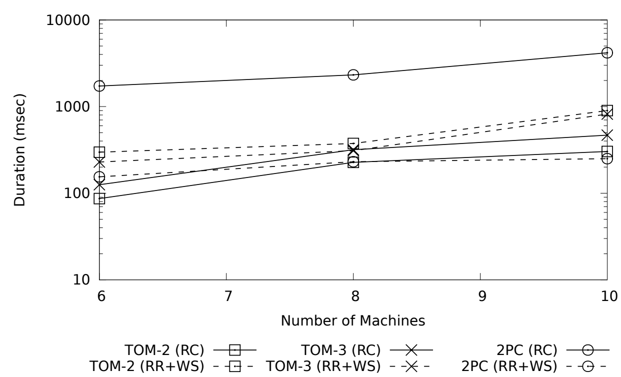
Figure 7: TPC-C (Replication Degree 2)



(a) Abort Rate



(b) Throughput



(c) Average Latency

Figure 8: TPC-C (Replication Degree 4)

which originate conflicts in the network and retransmissions, and additional processing load at the *JGroups* level. In the high contention scenario, however, 2PC's throughput is severely affected by deadlocks, which results in our solutions delivering around 40 times higher throughput.

Figure 7b depicts the throughput of the system using TPC-C with replication degree 2. Due to the high contention generated by this benchmark, also in these scenarios, the TOM-based solutions achieve striking throughput gains with respect to 2PC, which thrashes due to the frequent occurrence of deadlocks.

Figures 4b and 6b present the throughput using the *Radargun* benchmark with replication degree 4. In low contention scenario, we can observe that TOM-2 has the lowest throughput among the considered protocols. This is due to the fact that, increasing the replication degree, the number of messages exchanged by TOM-2 (which grows quadratically with the replication degree) induces a significant load on *JGroups*, whose performance significantly deteriorate (as we will discuss in the next section). However, TOM-3, whose asymptotic message complexity is linear with the replication degree (like in the 2PC-based solution), and which does not suffer of deadlocks (unlike the 2PC-based solution), achieves the best throughput with both the RC and RR+WS consistency levels. In high contention scenario, the performance of the 2PC-based solution is significanlty inferior to those achievable with replication degree 2, since the abort rate of this solution almost doubles when the replication degree changes from 2 to 4. Also at high contention, the throughput achieved by TOM-2 is lower with respect to TOM-3, due to the fact that the former generates a much higher network traffic with this degree of replication.

Figure 8b depicts the throughput of the system using TPC-C with replication degree 4. When contrasting these plots with those associated with replication degree 2, no significant differences can be observed at least for the case of TOM-based solutions (indeed, the performance of the 2PC protocol show an even worse thrashing phenomenon). Also the performance of TOM-2 and TOM-3 happen to be very close, once fixed a given consistency level. This is explicable considering that this benchmark generates computational intensive transactions, whose local execution is around 18 times larger than for the case of the *Radargun* benchmark. Therefore, the frequency of generation of TOMs, and the overall load for *JGroups*, is much lower in this benchmark when compared to *Radargun*. At this load level *JGroups* is far from saturation, and, consequently, the additional network traffic generated by TOM-3 with respect to TOM-2 has a negligible impact on performance.

3) Latency: Figures 3c and 5c show the average latency of the commit phase for *Radargun* with replication degree 2. With low contention, we note that the commit phase latency of all algorithms is similar. In high contention scenarios, however, the commit phase latency for 2PC becomes up to 2 orders of magnitude higher than for the TOM-based solutions. This is explained considering that the commit latency includes also the time necessary to detect deadlocks occurring during the commit phase, and that these become very frequent at high contention levels when using 2PC. The plots highlight also that the latency for the TOM protocols is stable in both high and low contention scenarios, contrarily to what happens when using 2PC, whose performance is very dependent on the workload of the system.

Analogous results are highlighted by Figure 7c, which shows the latency of the commit phase for TPC-C with replication degree 2. Also in this (high contention) scenario, the commit phase latency is significantly lower for the TOM-based protocols, being on average around one order of magnitude shorter than in the case of 2PC.

Figures 4c and 6c show the average latency of the commit phase for *Radargun* with replication degree 4. The plots highlight that the latency for TOM-2 is higher than TOM-3. As referred before, this happens due to the higher number of messages exchanged by the latter protocol. As before, the latency of 2PC is highly dependent of the contention of the system. In high contention, we have high probability of deadlock, which take a (relatively) large amount time to be detected, explaining the high commit latency for 2PC.

Figure 8c presents the latency of the commit phase for TPC-C with replication degree 4. The plots do not highlight significant deviations in the trends already observed when analyzing the scenario of replication degree equal to 2.

C. Discussion

Based on the previous results we can conclude that using TOM is beneficial in all the analysed scenarios. In addition, it is clear that the performance of 2PC is extremely dependent on the workload of the system; on the contrary, the performance of TOM is fairly stable both in low and high contention scenarios.

Interestingly, the TOM-3 solution outperforms the 2PC-based solution even in the most favourable settings for 2PC, namely very low contention and RR+WS consistency model. We recall that, in these settings TOM-3 incurs in two additional communication steps with respect to 2PC. Also, the deadlock probability is below 0.02% with 2PC (being zero of course for the deadlock-free TOM-based solutions). Despite such a low deadlock probability, the large penalty affecting 2PC upon the occurrence of deadlocks has a non-negligible impact on 2PC performance, which result around 20% lower than for TOM-3.

For what concerns TOM-2, its overall performance is poorer than that of TOM-3. Despite the fact that TOM-3 incurs in an additional communication step latency with respect to TOM-2, our results highlight that the quadratic message complexity of TOM-2 leads in practice (at least in our experimental platform) to a detrimental effect on performance of the Group Communication System, which offsets the possible gains associated with the reduction in the number of communication steps.

With *Radargun*, the difference between RC and RR+WS consistency model is almost negligible. This is justified by the fact this is a synthetic benchmark in which the probability that the same key is read and written by the same transaction is quite low. Hence, the write skew mechanism is not activated frequently. However, in the TPC-C results it is possible to see the effects of this mechanism.

VI. Conclusion

In this thesis we presented a solution for supporting partial replication in transactional in-memory distributed storage systems. The proposed solution is inspired by algorithms developed in the context of database replication, and later adapted to support weaker consistency models. The result consists of a genuine partial replication algorithm (in which only the replicas of the data updated during a given transaction participate in its commit phase) which distributes the load of the system among its nodes. This solution was implemented in *Infinispan* and its performance was compared against the native support offered by the platform. Unlike the native solution, based on the Two-Phase Commit protocol, ours prevents deadlocks. The performance evaluation shows that the proposed solution, based on total order multicast, achieves a throughput up to forty times higher than the native one.

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