Responsiveness and Consistency Tradeoffs in Interactive Groupware

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ABSTRACT

Interactive (or Synchronous) groupware is increasingly being deployed in widely distributed environments. Users of such applications are accustomed to direct manipulation interfaces that require fast response time. The state that enables interaction among distributed users can be replicated to provide acceptable response time in the presence of high communication latencies. We describe and evaluate design choices for protocols that maintain consistency of such state. In particular, we develop workloads which model user actions, identify the metrics important from a user's viewpoint, and do detailed simulations of a number of protocols to evaluate how effective they are in meeting user requirements.

Keywords: Replication, Consistency, Response Time, Performance Evaluation, Workload.

INTRODUCTION

Traditional interactive groupware, like chat, whiteboards, and text editors are becoming commonplace. In the future, we expect complex groupware like engineering CAD (Computer Aided Design), and DIS (Distributed Interactive Simulation) to be widely available. The interactive nature of such applications requires that the effect of a user's action is seen by himself as well as other users in a timely manner. However, the problem of providing quick response is becoming increasingly difficult as groupware is deployed in a wide-area distributed environment like the Internet, where high communication latencies are common. End-users are increasingly accustomed to direct manipulation user interfaces, which typically require response times of 50-100*ms*. However, due to the fundamental limitation of the speed of light, the round-trip delay to the far side of the planet is at least 200*ms*. In mobile wireless computers, intermittent connectivity can also cause large delays. As a consequence of these limitations, groupware systems have been exploring ways to provide interactive responsiveness independent of network latency.

The interactions across distributed collaborating users are supported by shared state. There is general agreement that replication of shared state has the potential to reduce response time for actions that manipulate this state, since a user's action can be executed on her local replica. In addition, it can reduce bandwidth requirements by batching of user actions [4], and provide fault tolerance. However, state replication leads to the problem of replica consistency due to the possibility of different ordering of updates at different replicas.

We assume a model in which the shared state is composed of a set of objects which are fully replicated at all the collaborating processes/users (A process is an instance of a groupware application running at a certain site). These objects are modified through *updates* that are *issued* by the collaborating processes. An update is a code fragment which can read and write a subset of the shared objects in a set, and is guaranteed to execute *atomically* at each replica. This model eliminates the need for groupware applications to explicitly use locks to achieve atomicity, and permits more flexibility in employing different consistency protocols. More details of the model and the motivation for it can be found in [3].

The protocols that are used by current groupware systems to order updates consistently at all replicas fall into two broad categories: *pessimistic* and *optimistic*. Pessimistic protocols usually delay the execution of an update until it is ordered consistently at all processes. An optimistic protocol allows a locally issued update to be executed immediately. The immediate execution of an update corresponding to a user action provides response time that is independent of communication latency between processes. However, there is a possibility that optimistic assumptions turn out to be false since two conflicting updates can be executed in different orders at different replicas. When this happens, updates have to be undone, and then redone in the *correct* order to get a consistent replica state (or updates can be transformed, as in dOpt [7]). This may cause surprise to the user, which we call *jitter*.

Optimistic protocols in some form have been used in many groupware research prototypes and protocols like dOpt [7], ORESTE [9], COAST [14], DECAF [16] and Villa [4]. However, there is no real quantitative evaluation, like measuring the response time and jitter, of these protocols. In this paper, our goal is to understand and evaluate certain de-

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sign choices for optimistic and pessimistic protocols in interactive groupware. We identify two contrasting classes of consistency protocols: *Dependent* and *Independent* and examine a pessimistic consistency policy for the former, and both optimistic and pessimistic policies for the latter. The two classes differ in how updates are timestamped to determine a global order, and how they commit updates. Commit is important in pessimism to determine when an update can be executed, and in optimism to know when an update will not need to be undone. To capture conflicts between updates of different users, we define two types of *contention*, *Object-level* and *Real*, which affect the behavior of these protocols. In particular, the following are the main contributions of this paper.

- We extend the user interaction model for graphical interfaces to include the concept of a *lookahead threshold*, which models the ability of the user to continue input actions while the previous actions are being executed. We use this to motivate why the issuing and execution of updates should be decoupled, and to develop a general model of user behavior for the synthetic workloads.

- We develop a detailed simulation of a protocol from each of the Independent and Dependent protocol classes. The simulations allow communication latency to be varied, and assign a cost to update execution and undo. They are driven by adaptive synthetic workloads, which allow control over parameters like the *lookahead threshold* and the amount of contention. The parameter values we use are motivated by real application scenarios. Metrics such as response time mean and standard deviation, stall count and stall time, message overhead and jitter count are used to understand the tradeoffs when choosing one of the protocols.

The benefits of quantitative evaluation are many. From a research viewpoint it can identify the weaknesses and strengths of current protocols, which can affect the direction of future research in consistency protocols. It can also be a tool for application developers to choose the appropriate protocol for their applications.

The next section describes the interactivity requirements in more detail and introduces the *lookahead threshold*. Subsequently, we describe the two consistency protocols we evaluate and how they are affected by contention. We then discuss the synthetic workloads, how they map to certain application scenarios, and motivate the metrics important for the evaluation. Next, we discuss the main results and how they can be used to choose the appropriate protocol for a certain situation. We then describe related work and conclude.

INTERACTIVITY REQUIREMENTS

In this section we give a more concrete definition of the interactivity requirements for groupware. For this, we build upon the considerable amount of research already done in single user graphical interfaces (for a good introduction see Collins [6], Shneiderman [15]).

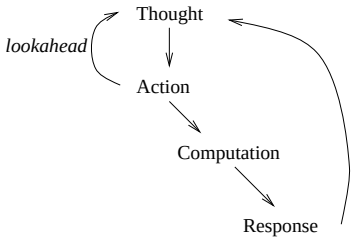


Figure 1: Extended human interaction model

The time interval between a user's input action and its response seen by the same user is the *Response Time* (RT). The key problem in interactive groupware is to keep the RT low enough so as to not differ significantly from single-user applications. This problem is made difficult because state consistency must not be overly compromised to achieve an acceptable RT.

User to User Time (UUT) is the time interval between a user's input action and its effect seen by a remote user. It is also important to minimize this quantity for interactive groupware, but this may not be as critical as low RT. However, in some scenarios, e.g., two users in the same virtual room involved in a war game, it is important to keep the ratio of UUT to RT small. The choices examined in this paper impact both UUT and RT, but our evaluation does not measure the impact on UUT.

The typical model used for user interaction is a cycle of *thought-action-computation-response*. The computation and response part of this cycle is responsible for the RT. This includes, translating the user *action* into an *update* on the shared state, and execution of this update on the local replica. Card [5] classifies tasks into categories based on the timing of this cycle. *Perceptual tasks* take less than 50-100ms and the user handles them without conscious processing. An example of this is tracking the motion of the mouse pointer.

Due to the very short duration of perceptual tasks, users do not necessarily wait for response from the previous task before going onto the next task. In terms of the human interaction model, we propose that tasks have a *lookahead threshold* (shown in Figure 1), which represents the number of actions that the user is willing to issue before the response to the first one is required. The lookahead threshold for perceptual tasks is expected to be non-zero. As tasks become longer duration this threshold will drop to zero. We now discuss the impact of a non-zero lookahead threshold.

Synchronous versus Asynchronous Processing

A non-zero threshold does not affect most single-user applications, in which RT is totally dependent on local processing. But in groupware, RT may depend on communication latency. This implies that a process can start computing the

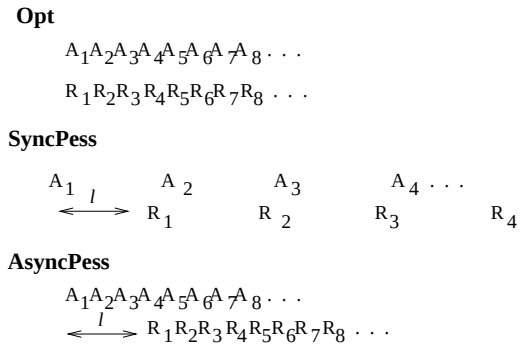


Figure 2: Some Action-Response Patterns

Protocol	Acceptable l (ms)	Unacceptable l (ms)
SyncPess	50	80
AsyncPess	140	240

Table 1: Response Time Expectations

next user action, if available, before the previous one has executed on the local replica. This asynchrony allows pipelining of the computation required for locally issued actions. Contrast this with a synchronous processing model, in which the process does not begin computing the locally issued action, until the previous action by it has executed on the replica.

To evaluate the impact of synchronous versus asynchronous processing, as seen by the end-user, we use a consistency protocol in which every update is sent to a central server, which totally orders all the updates. The optimistic policy will execute the update locally, before it is sent to the central server and therefore RT is independent of the network latency. The pessimistic policy waits till the update is returned by the central server, so RT, say l, depends on the round trip communication latency with the server. These policies can be combined with asynchronous or synchronous processing, to give four choices, SyncOpt, AsyncOpt, SyncPess, and AsyncPess. As synchrony or asynchrony has no impact when we execute optimistically, we are only left with three cases. Figure 2, shows some action-response patterns for the three cases. A_i is the instant when the computation on a user action begins and R_i is the instant when the response is seen locally.

We did an expert evaluation with two tasks, drawing lines and drawing free hand curves, to find the appropriate response time values. Optimism is the perfect case for response time, and we observed that the inter-action (most of the actions were mouse drag events) time was between 20-40ms — clearly a perceptual task. We then asked the experts to provide the minimum l values at which they started noticing the delay in response (acceptable), and when it became very irritating (unacceptable). These are tabulated in table 1. We can see that AsyncPess, which utilizes lookahead to pipeline computation, has a much higher unacceptable latency, implying that lookahead does occur, and can be utilized by the consistency protocol. On the other hand, even a response time of $80ms$ is unacceptable for SyncPess.

More detailed and rigorous user studies using more tasks are necessary to understand how the type of task affects these numbers. However, this preliminary result, which shows the significant effect of lookahead, motivates us to use an asynchronous processing model in the rest of the paper. Also, it shows that the value of the threshold can be an important factor when evaluating consistency protocols.

CONSISTENCY PROTOCOLS

The previous section discussed responsiveness. There is also a competing requirement, that of maintaining state consistency. We choose protocols that are representative of well-known protocols. A more comprehensive description of the design space of consistency protocols for interactive groupware is given in [3].

The shared state is composed of a set of objects that are fully replicated at all the processes in the collaboration. User actions are translated into *updates* by the process, which are then *issued* to the consistency protocol[1]. Each update can read and write a number of objects in the set. The system ensures that an update seems to execute *atomically* at a given replica i.e. reads and writes of two updates do not interleave. Also, as the *lookahead threshold* can be greater than zero, a process can issue updates even when its previously issued updates have not yet been executed locally.

Each update goes through the following stages: issue, timestamp at the source process, disseminate update with the timestamp to all replicas, execute at each replica. The timestamps define a *partial order* on all the updates issued by all processes. A total order is not essential as concurrent updates could be accessing different objects, and do not need to be ordered. The partial order must satisfy the *convergence criterion* i.e. any execution order of the updates that respects this partial order results in the same replica state. A pessimistic protocol always respects this partial order, while an optimistic protocol may have to reorder execution (using undo,redo), when it notices that it has violated the partial order. An update is said to have *committed* at a replica, when all the updates before it in the partial order have been received and executed. Therefore, a pessimistic protocol only executes an update after it has committed.

Other than the optimistic, pessimistic choice, a key aspect in which consistency protocols differ is: does the timestamp of an update depend on the objects accessed by it? The protocols for which the timestamp is independent of access are referred to as *Independent* protocols, and the one we use generates a total order using Lamport clocks [10]. With the optimistic policy, this protocol is similar to the ORESTE [9] protocol, except that our updates can read and write multiple objects. The other class is *Dependent* protocols, and the

[1] Sometimes referred to as the 'system'.

one we consider uses a 2-phase timestamping strategy (like 2-phase locking [2]). The update is executed at the source, and using the access information provided by the update as it executes, the source timestamps it. The motivation behind the use of dependent protocols is that they can generate a weaker ordering. Also, it is possible to commit an update even if some processes are not communicating with others. This is not possible with the Independent protocol using Lamport clocks, as before committing an update, a process needs to be sure that the clocks of all processes are greater than the timestamp of that update. However, dependent protocols may need to communicate with other processes while timestamping, so it slows down dissemination of updates. Fast dissemination is important for optimistic protocols, so we will only consider pessimistic execution with this protocol.

Before discussing the protocols, we define two pairs of read, write sets (r_1, w_1), (r_2, w_2) to be *conflicting* if and only if $r_1 \cap w_2 \neq \emptyset$ or $w_1 \cap w_2 \neq \emptyset$ or $w_1 \cap r_2 \neq \emptyset$.

Independent Protocols

These protocols use a Lamport clock at each process, which is incremented whenever a local update is issued, and is used along with the process number, to timestamp the update. These timestamps define a total order on all the updates. The update is then multicast to every process (including the source). Clocks are also modified whenever a timestamped remote update/message is received, using the usual modification rules. Every update received by a process is put in an uncommitted queue sorted in increasing order of timestamp. Each process also maintains a vector of timestamps which are estimates of the clock values of other processes (inferred from the messages received from those processes), and the minimum value in this vector is used to decide when an update in the uncommitted queue can commit. A committed update is removed from the queue. A timestamped heartbeat message is sent out by a process if it has not sent a message in a while, to ensure liveness of commit.

In the *optimistic* protocol (`optInd`), a process (say p) immediately executes all received updates. For each uncommitted update (say e), it also maintains the access sets (R_e, W_e) of the last time that update was executed. This information is changed whenever an update is undone and then redone. Suppose p receives an update u, which should have been ordered before a set of updates E, which it has already executed. To conform with the total order, p should undo E, however it is somewhat lazy. It first executes u, and if its access sets (R_u, W_u) *conflict* with R_e, W_e for any $e \in E$, some of the updates in E need to be undone.

For the *pessimistic* protocol (`pessInd`), updates are only executed after they commit, therefore no detection of conflicts is necessary.

Dependent Protocol

This protocol (`Dep`) uses locks, which are associated with mutually exclusive subsets of the objects. The larger the subset, coarser is the lock granularity. A lock has a version number, and the version numbers form a continuous sequence of integers starting with 0. These version numbers are used to timestamp updates associated with that lock, and this timestamp is used to order these updates. For example, suppose the current version number of lock A is 3, and lock B is 1. Then if user Alice issues an update (say u) which requires both lock A and B, then after acquiring both locks, this update will be timestamped with ((A,4),(B,2)). After timestamping, the locks are released, this update is multicast to others, and also inserted in the local uncommitted queue. Update u will be removed from this queue and executed only when update(s) with timestamps (A,3) and (B,1) have been executed. Note, that locks are only useful for timestamping, and are not required for committing an update. In our simulation of this protocol, we did not want to choose a specific lock management protocol, so we made a simplifying assumption. We assume that the process requesting the lock is omniscient and knows who last requested that lock. Therefore, it can send the lock request directly to that process, which eliminates the need to forward lock requests. To ensure no contradictory ordering information, locks that are acquired to timestamp an update are not released until the update is fully timestamped. This is similar to the 2-phase locking scheme used in databases.

Contention and Semantic Information

Due to social protocols mediating between users, in most collaboration scenarios where users are issuing actions concurrently, the concurrency is itself not a problem. However, it can cause problems for the consistency protocols. Also, social protocols do not guard against conflicts between concurrent updates when updates can have far-reaching indirect effects (like in some CAD scenarios), or when conflicts are deliberate (like in some multi-player games).

We define two kinds of contention which impact how these protocols perform. *Object-level Contention* (OC) between two concurrent updates occurs when their access sets (the read,write sets when they are executed in a total order that respects the partial order generated by the consistency protocol) are *conflicting*. Object-level contention limits the concurrency for `Dep` and can cause undos in `optInd`. Object-level contention between two updates does not imply that it was *really* necessary for the consistency protocol to order them. Therefore, we need to define a concept of *Real Contention* (RC). Informally, real contention between updates implies that if the ordering between them was removed from the partial order generated by the consistency protocol, that partial order would no longer satisfy the convergence criteria. Finally, in this paper we assume that when two updates with real contention are optimistically executed in the wrong order by `optInd`, and then corrected, it causes surprise to

Parameters	Text Editing	Engineering
N (number of users)	4	4
$threshold$	$0, 1, 2, 3$	3
update interval(ms)	$(400, 200)$	$(100, 50)$
numUpdates	1000	1000
latency (ms)	$100, \ldots, 1000$	$30, \ldots, 300$
heartbeat multiple	$1, 2, 3, 4$	3

Table 2: Parameter Values

the user, and we call this *jitter* in the user's interface (or view, in MVC terminology). Note, that in `optInd` , undo and redo is completely local and potentially very fast. By using techniques like double buffering we can hide the intermediate states of the view when undoing and redoing updates, and hence the user is not impacted by object-level contention which is not real. However, it is important to understand whether semantics of the shared state can be used to detect object-level contention that is not real, so that `Dep` can relax the partial order.

Note that we can conceptually split objects into multiple objects, and can then provide access information for these smaller objects. However, the lock (or object) granularity may not match the dynamic division of work the participants in a collaboration agree upon. Techniques like multi-granularity locking [2] can increase concurrency, but there are two problems which may limit improvements, or even worsen the situation. Firstly, in scenarios we consider with data-dependent access patterns, the granularity of what will be accessed by an update is not known beforehand, and so too many locks may be acquired. Secondly, having many locks may reduce the locality of acquiring locks by a process. For example, in the first sequence lock table given in [12], which can be used for text editors, insertion of every consecutive character causes a new lock to be acquired. Despite this, multi-granularity locking is a promising technique, and how to adapt it for timestamp-ordering protocols and its performance in a distributed environment needs more investigation, but is outside the scope of this paper.

Another scenario of OC which is not RC occurs when objects represent some physical entity, and there are physical constraints between them. For example, for collision detection in DIS, updates to the position of every entity require reading the positions of other entities in the neighborhood. However, the read value is discarded whenever collisions haven't occurred. In this case, the commutativity of two updates cannot be detected without knowing the state on which they will be executed.

EVALUATION SETUP

Workload

One of the main problems in evaluating the consistency protocols is that user input (both *what* is input, and *when* it is generated), can change with varying response time. We are not aware of any traces of user interaction with complex groupware that we can use to evaluate these protocols. As a first step in real evaluation of such protocols we construct adaptive distributed synthetic workloads. These workloads are adaptive in that they use the lookahead *threshold* to change the timing of the user input based on the response seen. A threshold of 0 means that a process does not issue a new update until the previous one has been locally executed i.e. each process only has 1 outstanding request at any time. Therefore a threshold of t means that a user can have $t+1$ outstanding requests, and we assume that the user stalls until the current lookahead falls below $t+1$. An alternative user model, in which the number of stalls are minimized by using the past response time information to increase the inter-update interval, may be more appropriate in certain situations, but is outside the scope of this paper. A uniform distribution with a certain *(mean, range)* is used to model the *inter-update interval*. *numUpdates* is the total number of updates issued by each process and *latency* is the one-way communication latency between processes. The *heartbeat multiple* gives the inter-heartbeat interval for the `Ind` protocols as a multiple of the *latency*.

The key characteristic of a workload is the number and type of objects in the shared set, and the access patterns of the updates issued by each process. We use two realistic collaboration scenarios to motivate these characteristics.

Text Editing *N* users are editing a document which is divided into sections, each of which is modeled as a shared object. Assume that `Dep` uses a lock per section. Depending on the situation, each user is editing his own section, or two users are editing different parts of the same section. To capture this behavior we use a parameter h, where *h=0* implies no contention of any sort, while *h=1* means that there is object-level contention between pairs of users. There is *no* real contention. The values of the other parameters are given in table 2.

Engineering Design This scenario considers shared objects hierarchically arranged in a tree. This can occur in the design of a complex physical model, like the example in [1], or the design of key-frames for animation of an articulated model (example in [3]).

Although it can be scaled to higher N values, we illustrate it with *N=4*. All the vertices in figure 3 represent shared objects. The leaf vertices represent primitive models which are combined hierarchically to create more complex models. Two models with the same parent model constrain each other, and therefore a write of one has to read the other. For example, an update which writes model 5 must read model 4. In this scenario, each process reads and writes two primitive models. For example, process P_1 reads and writes model 10 and model 11. With a certain probability p, a write of a model at level i, results in a write of its parent at level $i+1$.

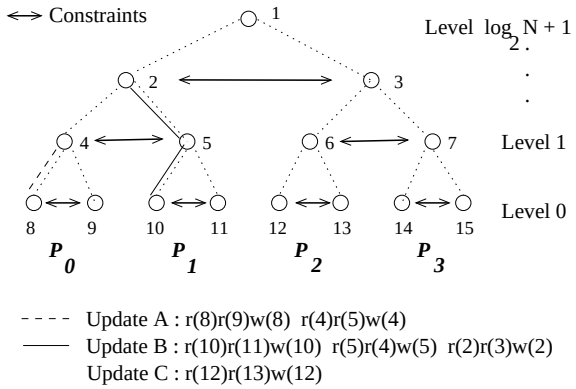


Figure 3: Forest Workload

Also, we can control the number of levels in the workload i.e. a maximum level of 2 means that there are 14 model objects, with model 2 and 3 not constraining each other. The number of the highest level is denoted by $h + 1$. The value of h controls the maximum possible object-level contention (max-OC), and is either 1 or 2. We simulate `Dep` with two lock granularities. For `DepCoarse`, there is one lock for each tree in the forest, and therefore we use $N/2^h$ locks. For `DepFine`, two siblings of a parent share a lock. As no locks are required for level $h + 1$, we optimize by only having $N/2^k$ locks for level k where $k < h + 1$. As children of the same parent share a lock, and every process moves from the bottom to the top when acquiring locks, there is no possibility of deadlock. p controls how much of the max-OC is realized (relative-OC), and is varied between $0.0, 0.2, \ldots, 1.0$. In figure 3, with *h=2*, only updates A and B cause object-level contention, while A and C, or B and C will contend in `DepCoarse`. The values of the other parameters are given in table 2.

Performance Metrics

We consider the following metrics.

1. Response time (mean and standard deviation) : Along with a low mean, a low deviation is also important to avoid user surprise due to wide variation in response time.

2. Local commit time (mean and standard deviation) : For the pessimistic protocols the commit time is the same as the response time. A low commit time is also good for an optimistic protocol as it reduces the possibility that an update may be undone a long time after it was initially performed.

3. Jitter Count : A subset of the local rollbacks/undos cause jitter. Note that rollbacks in `optInd` are completely local.

4. Number of messages of each type : Important for measuring the communication cost of the protocols. Other than the messages to disseminate the updates, which are the same for each protocol, the *extra messages* for `optInd`, `pessInd` are due to heartbeat messages, and those in `Dep` are due to lock request and reply messages.

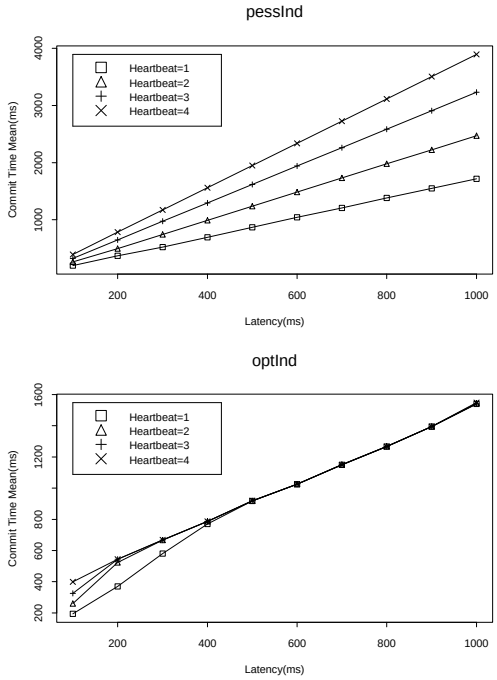


Figure 4: Commit time vs. Latency. Threshold=0

5. Stalled count and Stalled time : Stalled count measures the number of times the user had to stall because the previous $threshold + 1$ updates had not been locally performed. Stalled time is the mean time for which the user stalled.

6. Total execution time : Measures how long the users took to finish their tasks.

RESULTS

We simulated the protocols with both the text editing and engineering design workload. In this section we summarize some of the interesting results.

Text Editing

Due to the large number of parameters, we highlight the effect of the *threshold* and *heartbeat multiple* and then fix their values to reasonable levels. A scatter plot of the commit time versus the threshold, for all the protocols, showed that it was *usually* not affected by the lookahead threshold value. This may be expected as the threshold value affects when an update is issued, but should not affect the commit time of an already issued update. However, when *threshold=0* for `pessInd`, the commit time was sometimes much larger than when *threshold* > 0. Also, it was much larger than the

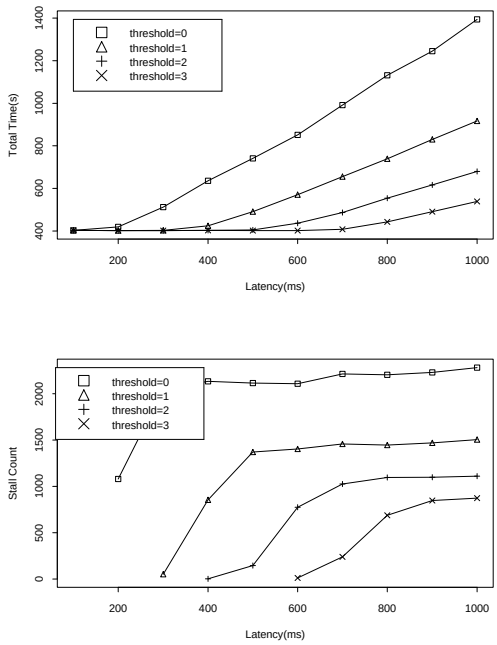


Figure 5: Total time and Stall count for Dep ,h=1

commit time for optInd with *threshold=0*. To explain this, figure 4 shows the effect of heartbeat multiple and latency on commit time for pessInd and optInd when *threshold=0*. For optInd , the effect of heartbeat frequency decreases as latency is increased. This is because the inter-update interval is much lower than the latency so heartbeats are not really needed. However, as pessInd executes updates pessimistically, it stalls after issuing each update, and hence heartbeat messages are very important to pick up the slack in message frequency. It can be seen that with *heartbeat=1* the commit is almost as fast as that of optInd , however in this case the number of heartbeat messages was of the order of the total number of updates. This gives us the following observation.

Observation 1 *When* threshold=0*, increasing the heartbeat rate decreases the response time and total time for* pessInd *significantly. However,* optInd *is unaffected by heartbeat rate at high latencies.*

Next, we looked at how threshold affected the total time of the task. As expected, it did not affect optInd , and Dep when *h=0*, but had a strong effect on pessInd , and Dep when *h=1*. Figure 5 shows the effect of threshold and latency on Dep when *h=1*. As expected, the total time for the task decreases with increasing threshold value. Increase in total time with latency is due to increasing number of stalls (up to a certain maximum, dependent on the threshold value) and increasing time for each stall. For *threshold=3*, no process stalls until *latency=600ms* and therefore the total time taken remains constant until then.

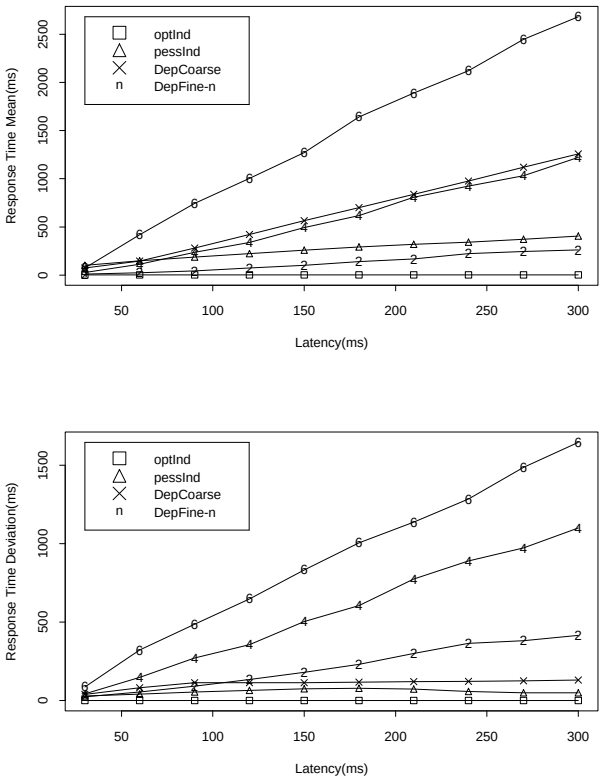


Figure 6: Responsiveness vs. Latency. h=2

Observation 2 *In a task with a high value of threshold, the user can perform well even at high latencies, because of the lower total number of stalls and the smaller mean time for each stall.*

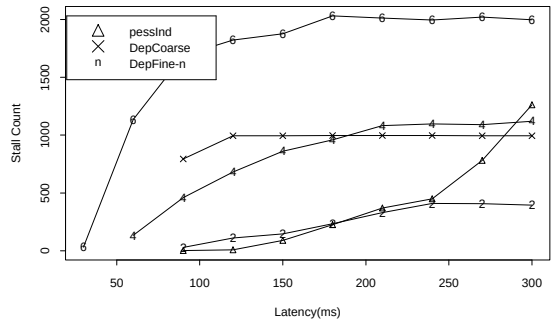
The results pertaining to varying contention are better examined in the engineering design experiments.

Engineering Design

We fixed the *threshold=3* and *heartbeat=3*. With no max-OC, i.e. *h=0*, the performance of optInd and DepCoarse is equivalent, as neither communicates with other processes before executing a local update. Similarly, when $h = 0 \vee p = 0$, i.e. there is no OC, optInd and DepFine are equivalent. In figures 6 to 9, DepFine-n refers to the DepFine protocol when $p = 0.n$. The values of p, h have no effect on pessInd . In the following observations, *low* max-OC refers to *h=1*, *high* max-OC to *h=2*, *low* relative-OC to $p = 0.2, 0.4$ and *high* relative-OC to $p > 0.4$. We first examine metrics in which p, h do not affect optInd [2].

Figure 6, shows that pessInd gives a lower response time than DepCoarse beyond a latency of $60ms$. DepFine with $p \leq 0.2$ is better than pessInd , however it dete-

[2] Although undo and redo do impact these metric values, the effect was insignificant.



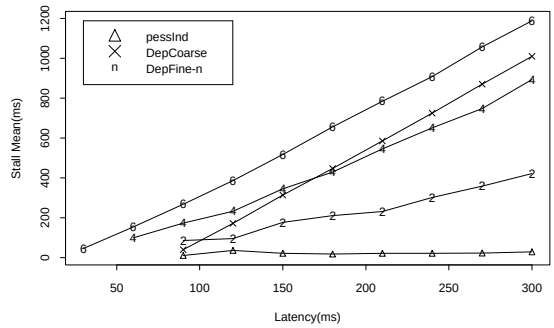
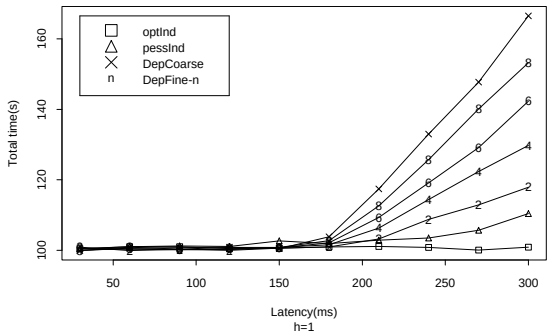


Figure 7: Stall vs. Latency. h=2



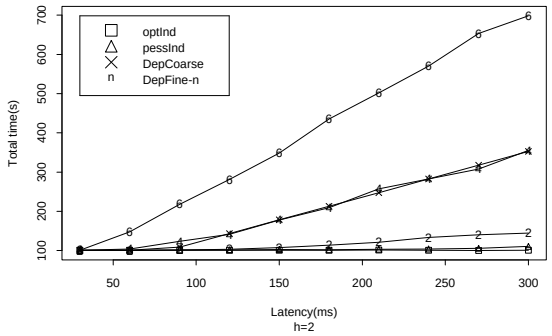


Figure 8: Total time vs. Latency

riorates quickly with increasing p. In fact, for $p > 0.4$, DepFine performs much worse than DepCoarse, because it is acquiring multiple locks in sequence for every update, while DepCoarse only acquires one lock of coarser granularity. This gives us the following observation.

Observation 3 *When max-*OC *is high and relative-*OC *is low,* DepFine *has lower mean response time than* DepCoarse *and* pessInd*. However, with high relative-*OC*,* DepFine *can have higher mean response time than* DepCoarse *and* pessInd*, and this difference increases with increasing latency.*

Looking at the standard deviation of response time, we see that it is lower for pessInd than both DepCoarse and DepFine. Also, the deviation for pessInd and DepCoarse is relatively independent of latency, even though the variation in latency is increasing with increasing mean latency. This can be attributed to the average of many independent random variables having a lower deviation than each of them alone. However, with $p = 0.2$, DepFine has a higher deviation than both DepCoarse and pessInd, even at very low latencies, because for each update it may have to acquire anywhere between 1 and 3 locks.

Observation 4 *Even with high max-*OC *and low relative-*OC*,* DepFine *can have a higher response time deviation than* DepCoarse *and* pessInd*, and this difference increases with increasing latency.*

Figure 7 shows how the stall count and mean vary with latency. The stall count of optInd, DepCoarse with *h=0*, and DepFine with *p=0* is zero. The stall count for pessInd rapidly increases after *latency=240ms*, because the lookahead can no longer suppress the effect of the latency. However its stall mean is relatively stable and is around $25ms$. In our user model, in which the user stalls when her lookahead exceeds the threshold, the relative importance of stall count and stall mean needs to be investigated i.e. does the user want to wait more number of times or wait longer each time. The stall count for DepCoarse stabilizes at $N * numUpdates/(threshold + 1)$.

Observation 5 *The stall count of the* Dep *protocols is limited by the* threshold*, while that of* pessInd *keeps increasing with latency. However, the mean time for the stall is independent of latency for* pessInd*, but keeps increasing for the* Dep *protocols.*

Figure 8 shows how the total time varies with latency with *h=1,2*. Even though the response time mean for pessInd was usually higher than the Dep protocols at low contention, the total time does not show this. This is because the lower stall mean of pessInd compensates.

Observation 6 *For low max-*OC *and* $latency \leq 180ms$*, the choice of the protocol has negligible effect on the total time taken to perform a task. However, with high max-*OC *and low relative-*OC*, the* Dep *protocols can perform significantly worse than the* Ind *protocols.*

Note that we have not modeled the increasing errors, or user

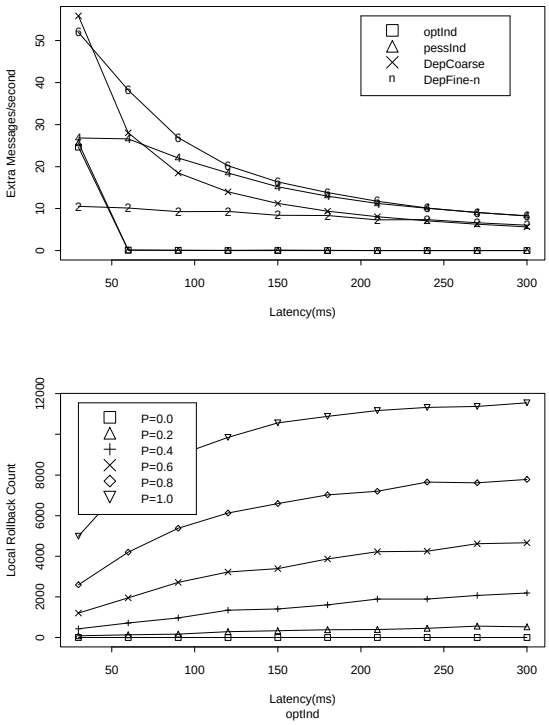


Figure 9: Extra Messages, Rollback count. h=2

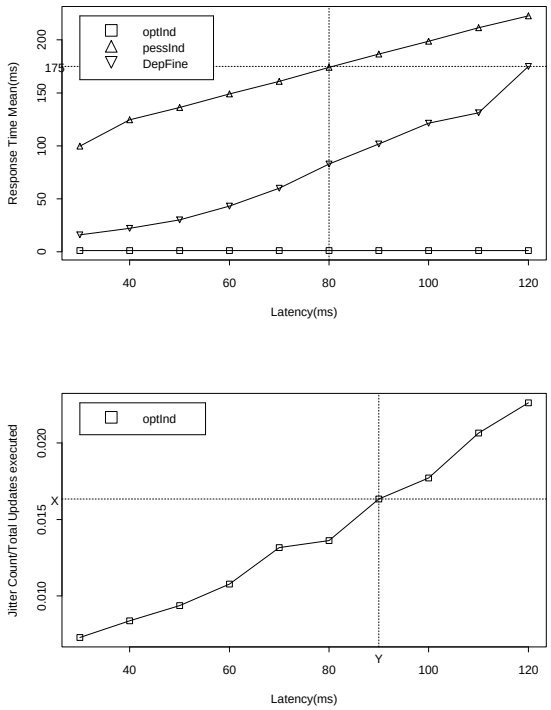


Figure 10: Protocol comparison. h=2,p=0.3

frustration that may occur when response time increases beyond a certain value. Therefore, acceptable response time values for the task need to be considered along with this total time information when choosing a protocol.

From figure 9, we can see how many extra messages are sent per second, by each of the protocols. For the `Ind` protocols at a very low latency, the heartbeat interval ($3 * latency$) is lower than the inter-update interval, so a lot of extra heartbeat messages are sent. Otherwise, the `Ind` protocols have 0 extra messages. The extra messages for the `Dep` protocols slowly decline as latency increases, as the total time to perform the task is increasing. Also, the same figure gives the number of rollbacks/undos for `optInd` as the latency and relative-OC increases. Note that how many of these rollbacks cause jitter is very dependent on the collaboration scenario. However, the amount of jitter that is tolerable, is a very important factor in determining whether `optInd` is useful for a certain collaboration scenario.

Discussion

An important question is, given the scenario, how do we apply the preceding information to decide which protocol to use. We illustrate with an example. Suppose we know that *h=2,p=0.3*, that the latency can vary between $30ms$ and $120ms$, and 50% of the rollbacks cause jitter. Figure 10 shows the mean response time for `optInd`, `pessInd`, `DepFine`, and the fraction of the total updates executed which caused jitter, which we call the *jitter fraction*. If the maximum tolerable jitter fraction is greater than 0.022, `optInd` is clearly the best because of its instantaneous response. If the maximum tolerable jitter fraction is a value x, less than 0.022, we have a choice to make. Let y be the latency value corresponding to this value x. We can use `optInd` when the latency is less than y, and then dynamically switch to `pessInd`. This can be easily done because the choice to switch from `optInd` to `pessInd` and vice versa can be made *locally* by each process. However, if we also cannot tolerate a mean response time greater than $175ms$, we will have to use `DepFine` beyond a latency of y. As it is hard to dynamically switch between the `Dep` and `Ind` protocols without coordination between all the processes, which may not be possible, we may then have to use `Dep` for the whole collaboration.

RELATED WORK

Greenberg and Marwood [8] qualitatively discuss the impact of different concurrency control schemes, including optimistic and pessimistic protocols, on certain collaboration scenarios. They observe that social protocol between participants make conflicts rare, and in many cases it is possible for users to notice conflicts and manually repair them. For the next generation of collaborative applications, we expect that conflicts usually occur due to secondary effects of user actions, for example, automatic constraint evaluation in en-

gineering design, and collision detection in distributed interactive simulation. In such scenarios, conflicts will be more common, and we cannot expect the user to manually fix the state.

For replicated state, two types of consistency protocols have typically been used. Explicit locking approaches use locks for atomicity and concurrency control, like DistView [13]. Ordering based approaches need an associated commit protocol. The `Ind` protocol is similar to ORESTE [9]. DECAF [16] uses a primary copy commit protocol in which an update issuing process only needs to talk to the primary copy processes for the update to commit. A protocol in which the primary copies assign timestamps can also be constructed, and the `Dep` protocol is a dynamic variation of this, in which the primary copies can move.

Finally, there has been some studies to understand how poor response time affects human performance for single user tasks. MacKenzie and Ware [11] use a simple target acquisition task in which the user has to move the mouse cursor into a rectangular target. Their user studies show significant increase in both the time to perform the task, and the error rate, as response time is increased.

CONCLUSION

We have described and evaluated design choices for consistency protocols in interactive groupware deployed in a wide-area distributed environment. For such high latency environments, the concept of a *lookahead threshold* for user actions is very important for a real evaluation of protocols. This models the users ability to issue a number of actions without waiting for the first action to complete. We have described two classes of protocols that can be used to consistently execute the user updates at all replicas. With a novel workload model, we have evaluated these protocols along a number of dimensions and have discussed how to use the observed metric values to choose the appropriate protocol.

Although it is very important to quantitatively evaluate consistency protocols, the evaluation problem is incredibly hard. Firstly, it involves construction of workloads for a large class of applications and different usage scenarios for these applications. These workloads need to be adaptive like a user i.e. they should change according to the behavior of the system. Secondly, it is important to formally or informally validate these workloads, otherwise the results might be misleading. Thirdly, the relative importance of the metrics is not well understood and nor is the design space of such protocols. The answers to some of these questions are obviously highly dependent on the user. Therefore, it is important to get enough insight from the evaluation data, so that a very high-level interface can be offered to the user to tune the behavior of the protocols at run-time. This also brings up the question, can we dynamically switch between protocols at run-time? The goal of this paper is not to provide a definite answer to all these questions, but to start us down the path of finding the answers.

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