A Migrating-Home Protocol for Implementing Scope Consistency Model on a Cluster of Workstations

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Abstract *The performance of a software Distributed Shared Memory relies on an efficient memory consistency model, and a suitable protocol for implementing the model. This paper studies a new concept of a migrating-home protocol for implementing the scope consistency model. In this protocol, the home, which is the location of the most up-to-date copy of each memory page, can change among processors. We implement this idea on a cluster of UltraSPARC I model 140 workstations with ATM network. The migrating-home protocol outperforms the home-based approach and adapts better to the memory access patterns for most applications. It reduces communication overheads in forwarding page updates among the processors. Page faults can also be handled in a more efficient way. These factors reduce a considerable amount of data communicating within the cluster.*

Keywords: Cluster Computing, Scope Consistency, Migrating-Home Protocol

1 Introduction

Cluster or network of workstations is becoming an appealing platform for cost-effective parallel computing. But their usability and programmability depend much on the programming environment. One of the most popular parallel programming paradigms is software *Distributed Shared Memory* (DSM), which offers the abstraction of a globally shared memory across physically distributed memory machines.

In a DSM system, multiple copies of memory pages reside in different machines. A *memory consistency model* formally specifies how the memory system will appear to the programmer [1]. Memory consistency models affect the efficiency of DSM. The first DSM system, *IVY*, adopted *sequential consistency* (SC) [2]. However, its performance was poor due to excessive data communication among machines. Later systems, such as *TreadMarks* [3], improves its efficiency by using the more relaxed *lazy release consistency* (LRC) model [4]. The *Midway* system [5], on the other hand, employed *entry consistency* (EC) [6], which is more efficient than LRC. Unfortunately, the programming interface associated with EC is not easy to use. S*cope consistency* (ScC) has thus been proposed [7], aiming at achieving good programmability and performance.

To implement ScC, two *protocols*, namely the *home-based* and the *homeless* protocols, can be employed [8]. For the home-based (or fixed-home) protocol, a machine in the cluster is designated to keep the most up-to-date copy of every logical page in the system. Hence, when a processor requests a page, it only needs to communicate with the home. In comparison, to serve a page fault under the homeless protocol, a processor must send out requests to every processor which has updated the page, collects the updates from the processors, and applies the updates in sequence to obtain the most updated version of the page. Although both protocols adopt the *diffing* technique to handle the *false sharing* problem [3], research [9] shows that the home-based protocol outperforms the homeless one since the home-based protocol incurs less communication in the network.

This paper discusses a *migrating-home protocol* for implementing ScC. In this protocol, the location storing the most up-to-date copy of each page is changeable among the processors, so that in most cases, the processor requiring the page becomes the new home of that page. Processors send out short *migration notices* to notify others about the home change. This allows our protocol to perform less diffing operations and fewer lengthy diffs are sent among the machines. The protocol further reduces communication overhead by concatenating mul-

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tiple migration notices with the remaining diffs as a single message for transmission. It can also handle page faults more efficiently since more page faults can be served locally without communicating with other processors. All these factors help to reduce the total amount of data communicating within the cluster effectively.

We implement the migrating-home protocol on the JUMP system, which runs on a cluster of 8 UltraSPARC I model 140 workstations with ATM networking. Four benchmark applications with different memory access patterns are tested. The migrating-home protocol adapts to the access patterns of most applications better than the original home-based protocol. This is shown by the testing results, in which the migrating-home protocol speeds up the execution time over the home-based approach for most applications. The maximum reduction in execution time is 67.5%. In addition, the migrating-home protocol can save up to 97% of the total amount of data sent within the cluster.

For the rest of the paper, Section 2 introduces the ScC model and the home-based protocol for implementing the model. Section 3 describes our migrating-home protocol in detail. Section 4 discusses the implementation of JUMP, the testing environment and benchmark applications. Section 5 addresses the testing result by comparing JUMP and its counterpart using the home-based protocol. Section 6 summarizes our conclusions.

2 Scope Consistency (ScC) and the Home-Based Protocol

In this section, we briefly describe the scope consistency model [7] and the original home-based protocol [8] used to implement scope consistency to place the ground of our research.

The objective of *scope consistency* (ScC) is to provide high performance like EC and good programmability like LRC. This is achieved by the use of the *scope* concept, which reduces the amount of data updates sent among processors, and fits naturally to the synchronization provided by the lock mechanism.

In ScC, a scope is a limited view of memory with respect to which memory references are performed. Updates made within a scope are guaranteed to be visible only in the same scope. For example, in Figure 1, all critical sections guarded by the same lock comprise a scope. In other words, the locks in a program determine the scopes implicitly, making the scope concept easy to understand. The *acquire* operation *opens* a scope, while the *release* operation *closes* the scope. From the above concepts, the consistency rule of ScC is defined as follows: *When a processor Q opens a scope previously closed by another processor P, P will propagate the updates made within the same scope to Q.*

As an illustration, consider the example in Figure 1 again. Under ScC, *P0* does not propagate the updates of *x* and *y* to *P1* (while *P0* does under LRC), since the updates are not in the same scope (Scope 2). Therefore, the reads of *x* and *y* made by *P1* may give results other than 1.

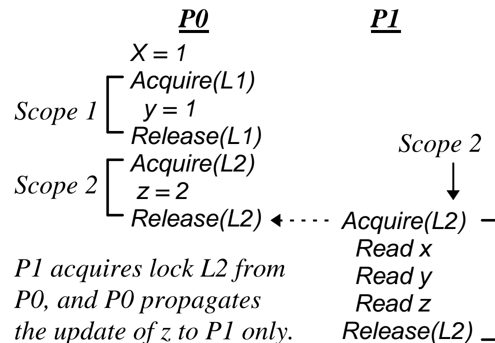

Figure 1: An example for ScC.

ScC is more efficient than LRC, since ScC does not propagate the updates made in scopes other than the one being opened, while LRC propagates all the updates before the release. Moreover, ScC provides good programmability, since it retains the same programming interface as LRC. It does not require explicit binding of variables to locks as EC does. Thus we consider ScC a promising memory model for DSM.

The original implementation of ScC is based on the *home-based protocol* [8], with the *diffing* technique to handle *false sharing* [3]. For each page in the memory, the protocol assigns a processor in which the most up-to-date copy subsides. This processor is the *home* of the page, fixed at the start of application execution. All other processors will send the page updates to the home at synchronization time. Upon a page fault, they can get a clean copy of the page by requesting the home processor. While in homeless protocols, no processor is responsible to keep the most updated copy of the page. To serve a page fault, a processor requests all other members in the cluster to send the updates made by each of them, and then apply these updates

in sequence to create a clean copy of the page. This introduces a high communication overhead and complicates the implementation as well. For example, timestamps are needed for the diffs to identify the order of the updates.

To illustrate the home-based protocol, we focus on a basic scenario of shared memory access in Figure 2. Assume variable *X0* is in page *x*. Processor *P0* tries to write to *X0* and generates a page fault. *P0* then requests the page from *P2*, the home of *x*. *P2* replies with a copy of the page. When *P0* gets the page, it makes a duplicate called a *twin* and performs the write. Later, at the release of lock *L*, *P0* compares the updated page with its twin and sends out the page difference, known as the *diff*, to *P2*. Finally, *P2* receives the diff and acknowledges *P0* with a *diff grant* message.

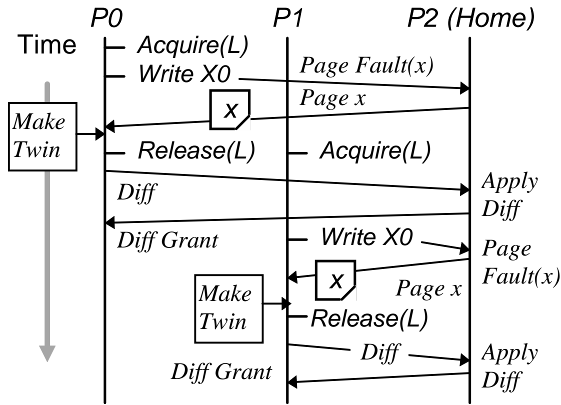

Figure 2: An Example for the Home-Based Protocol.

3 The Migrating-Home Protocol

Although the home-based protocol described in Section 2 is more efficient than the homeless one, the concept of a fixed home can hinder the efficiency of the protocol. In this section, we study the *migrating-home protocol*, in which the home is changeable among processors. From here onwards, we refer to the home-based protocol as the fixed-home protocol, as opposed to the migrating-home protocol.

3.1 The Migrating-Home Concept

The fixed-home concept does not adapt well to the access patterns of many applications. Its inflexibility introduces a pair of diff and diff grant messages communicating among processors, as shown in the previous example in Figure 2. These messages can be saved if we grant the home to *P0* when *P2* serves the page fault. As *P0* has the most updated copy of page *x*, the diff and diff grant messages need not be sent, as shown in Figure 3. This is the migrating-home concept: *When a processor asks for a page from its current home processor, the requester can become the new home.* Figure 4(a) shows this concept graphically. In the diagram, the circular "token" denotes the home of page *x*. It is moved from *P2* to *P0* to indicate the change of home.

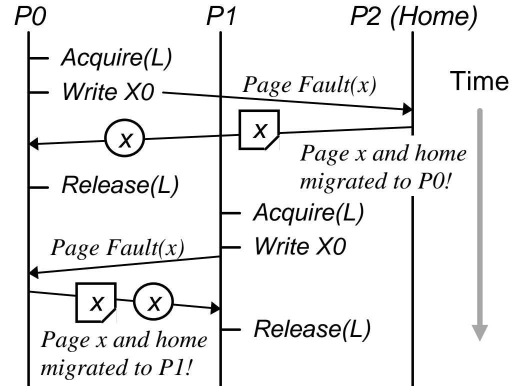

Figure 3: An Example Illustrating the Migrating-Home Concept

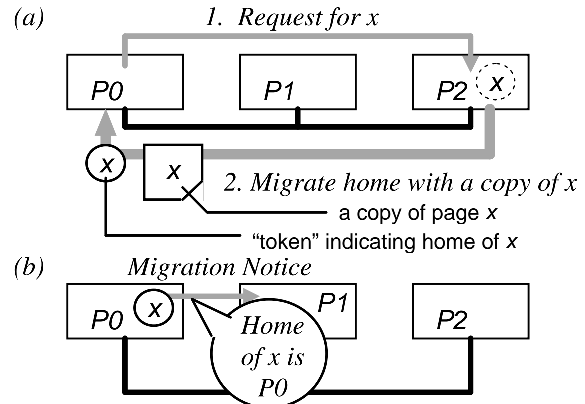

Figure 4: The Migrating-Home Concept: (a) Home Migration, (b) At Lock Release.

However, *P1* may request page *x* after the home change, as shown in Figure 3. It may get an outdated copy if it requests the page from the previous home *P2*. To avoid this, *P0* needs to send a *migration notice* to all the other nodes at synchronization time, as shown in Figure 4(b). This replaces the lengthy diffs, which can be the same size as the page itself. Thus the migrating-home protocol reduces the number of bytes sent within the cluster. Moreover, as a DSM application can access many pages, the migration notices can be merged to form a single message to reduce the communication startup cost.

3.2 Solution for False Sharing

To deal with false sharing, the migrating-home protocol also uses the diffing technique, with additional rules to maintain memory consistency. When two processors ask the home for the same page before synchronization, the first becomes the new home, as shown in Figure 5(a). The late requester will receive a copy of the page from the previous home and also the new home location (Figure 5(b)). Therefore, it can send the diff to the new home. Under ScC, the copy obtained by the late requester is clean if the two processors do not access the same variable. Also, the communication overhead of the diff can be reduced by concatenating it with the migration notices before sending when they have the same destination.

Table 1: Table showing the Major Events and Actions in the Migrating-Home Protocol.

Event	*Action*
Page fault	Send a request to the home of page
Request for page *x* from processor *P* received	1) If I am home of *x*, grant a copy of *x* to *P*. If (set of processors getting a copy of *x* = set of processors that have sent diff for *x*), then migrate the home to *P*, and I become the previous home of *x*. Record the ID of processor *P* otherwise. 2) If I am the previous home of page *x*, then grant a copy of *x* to *P*, and tell *P* about the new home. Record the ID of processor *P*. 3) If not 1) or 2), reject request, tell *P* to ask the new home.
Lock release	For every page *x*: 1) If I am home of *x*, send migration notice to every other processor. 2) Otherwise, send the diff of *x* to its home.
Diff of page *x* received	I am the home of *x*, thus, send back the diff grant message.
Migration notice of page *x* received	1) If I am home of *x*, reply sender with the processors that have received a copy of *x* from me. Cancel the previous home flag. 2) Otherwise, note the home change.
Getting the page *x*	1) If home not granted, make a twin of *x* before writing the page 2) Otherwise, just write on the page.

Table 1 shows the algorithm discussed above in tabular form. For further illustration, we give an example as shown in Figure 6. *P0* first writes to variable *X0*, causing a page fault for *x*. It requests *P2* for the page. *P2* sends *P0* a copy of *x* and grants *P0* the new home of *x*. Then, before *P0* releases lock *L0*, *P1* writes to *X1*, which is in page *x*, too. In this false sharing situation, *P1* asks *P2* for the page and gets the copy, in which *X1* is still clean. However, *P2* cannot grant *P1* as the home of page *x*, since *P2* is no longer the home. Instead, *P2* informs *P1* that *P0* is the new home of the page, so that *P1* can send the diff to *P0* at the release of lock *L1*.

At the release of *L0*, *P0* sends a migration notice to all processors. *P2* replies by notifying *P0* the processors that have got a copy from *P2*. *P0* then decides whether it allows home change when it receives a fault on that page later. If some processors have not sent the diff, such as *P1* in this example, home migration cannot take place.

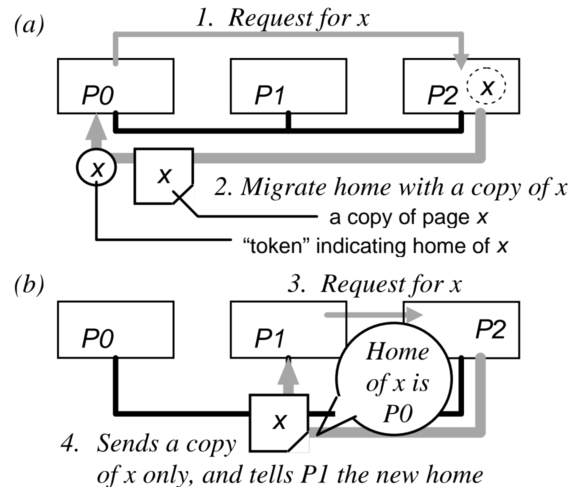

Figure 5: Handling the False Sharing Problem.

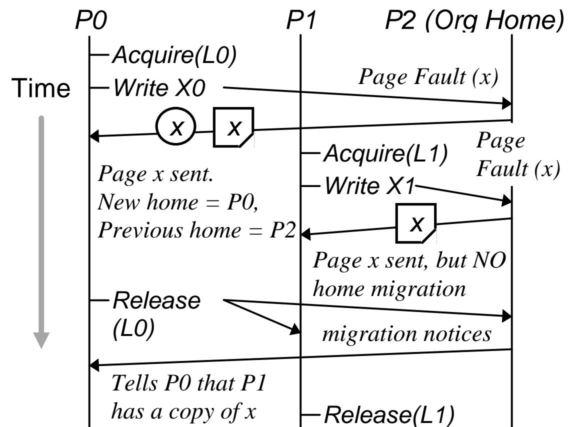

Figure 6: The Migrating-Home Protocol with False Sharing Support

Moreover, after *P2* replies the migration notice from *P0*, *P2* will reject any page fault request of

x from other processors, because *P2* has no way to inform the new home *P0* again. In such case, *P2* will reply the requester the new home of the page. This rarely happens, since all the processors usually should have received the migration notice. Thus they should have known the new home location.

4 Implementation and Testing

We have implemented the migrating-home protocol by modifying the JIAJIA DSM system [9] to form the JUMP (JIAJIA Using Migrating-Home Protocol) system. JIAJIA is a user-level runtime library built on UNIX. It implements ScC using the home-based protocol, and it handles false sharing by the diffing technique.

We run JUMP on a cluster of 8 UltraSPARC I model 140 machines connected by a 16-port FORE ATM ASX1000 switch. The port bandwidth can achieve 155Mbps. Each workstation has 64MB of main memory with 8KB page size, running Sun OS 5.6.

To test the performance of JUMP, we write four benchmark applications in C, as described in Table 2. We execute each program with various problem sizes on 2, 4 and 8 nodes. We also run the programs on the original JIAJIA implementation using the same environment.

5 Results and Analyses

This section analyzes the performance of the migrating-home protocol on the JUMP system in terms of execution time, network data traffic and the number of page faults generated.

5.1 Execution Time Analysis

The decrease in execution time in JUMP as compared with JIAJIA is application-dependent as shown in Figure 7. Overall, JUMP performs much better over JIAJIA on most applications. For ME, JIAJIA runs 10.8-35.5% faster for problem sizes with $n \le 2M$. When $n = 4M$, JUMP runs the program in less than half the time needed by JIAJIA. JUMP even beats JIAJIA by running up to 67.5% faster on LU.

In RX, JUMP outperforms JIAJIA steadily by no more than 9.8%. The result is similar for MM, in which JUMP is at most 9.0% faster. The only exception is when JUMP executes MM with small matrices (n = 64 or 128) using 8 processors, at which JUMP suffers a small performance degradation of 5% or less.

5.2 Communication Analysis

Table 3 summarizes the number of messages (*# Msgs*) sent for each application under JUMP and JIAJIA, together with the total number of bytes communicated during the execution (*MBytes*) for the 8-processor case. Except for ME, JUMP sends a larger number of messages than JIAJIA for most of the data points. However, these messages are short ones, as JUMP sends fewer bytes than JIAJIA. Also, for LU and RX, the difference in the number of messages sent between JUMP and JIAJIA is large for small problem sizes. However, this gap becomes closer or even disappears for larger problems. This is because we take advantage of the short migration notices by concatenating them together, as discussed in Section 3.2.

A third point observed is that the migrating-home protocol in JUMP sends fewer bytes than the fixed-home protocol in JIAJIA, especially on large problem sizes. For example, JUMP sends 42-66% fewer bytes than JIAJIA for the ME application. JUMP even achieves a 97% save for LU on large problem size (n = 1024). This reduced amount of data communication accounts for the performance improvement achieved by JUMP.

Table 2: Description of the Four Testing Applications

Name	*Arg.*	*Problem Description*
MM	*n, p*	Matrix Multiplication of two $n \times n$ matrices using p processors
LU	*n, p*	LU Factorization on an $n\times n$ matrix using p processors
ME	*n, p*	Merge Sort on n integers using p processors (merge p sorted lists)
RX	*n, p*	Radix Sort on n integers using p processors

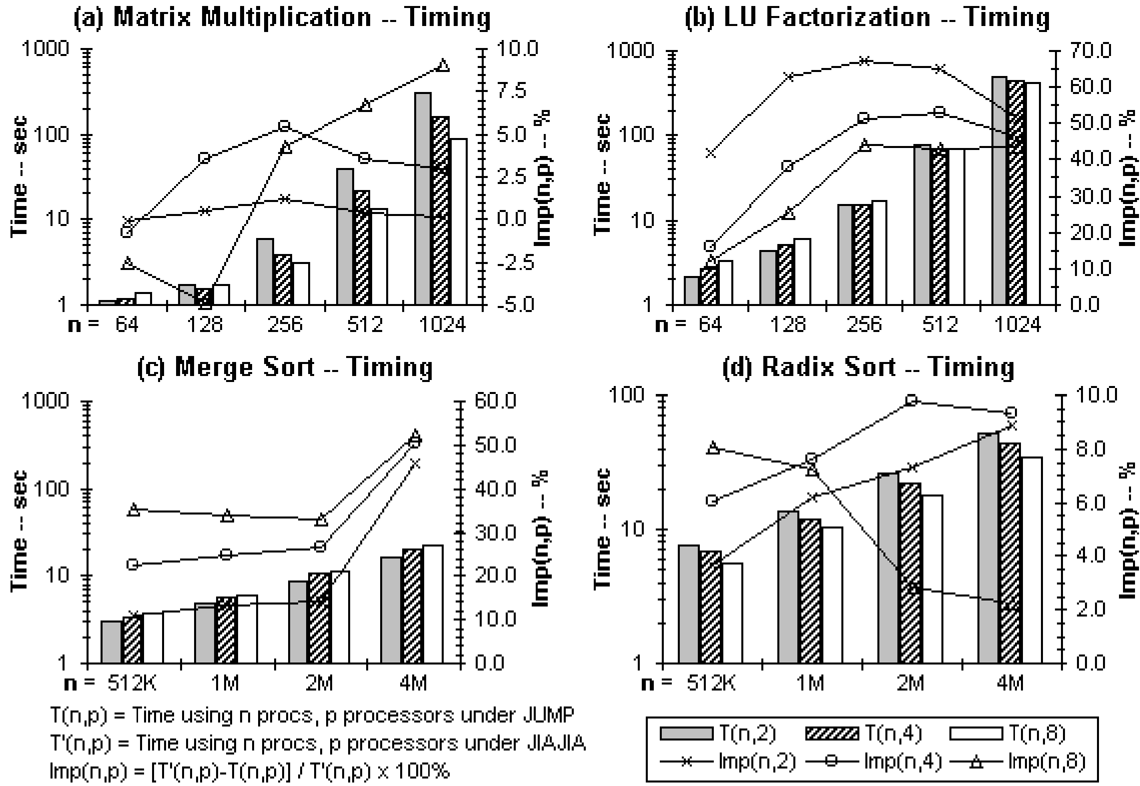

Figure 7: Performance Improvement of the Testing Applications
(Note that the bar chart, which shows the execution time, is in log scale.)

Table 3: Comparison of Communication and Page Fault Statistics between JUMP and JIAJIA (p = 8)

Appl. Name	*Size (n)*	*JUMP*						*JIAJIA*					
		# Msgs	*MBytes*	*PF1*	*PF2*	*PF3*	*Total*	*# Msgs*	*MBytes*	*PF1*	*PF2*	*PF3*	*Total*
MM	64	696	0.746	12	45	77	134	471	0.715	8	49	73	130
	128	1288	0.681	64	0	91	155	455	0.993	8	56	77	141
	256	1897	2.838	228	0	392	620	1236	4.031	32	196	358	586
	512	3829	11.216	912	0	1568	2480	3402	17.349	128	784	1428	2340
	1024	11557	44.731	3648	0	6272	9920	11208	69.315	512	3136	5712	9360
ME	512K	1503	5.073	800	0	608	1408	1645	12.017	128	672	560	1360
	1M	2719	10.134	1600	0	1216	2816	3213	24.035	256	1344	1120	2720
	2M	5151	20.256	3200	0	2432	5632	6349	48.066	512	2688	2240	5440
	4M	10015	40.500	6400	0	4864	11264	17944	118.473	1024	4165	7185	12374
RX	512K	6986	22.350	2123	0	2680	4803	5680	33.641	325	1896	2279	4500
	1M	10733	39.010	3952	0	4684	8636	9809	62.911	578	3469	4033	8080
	2M	18294	72.479	7593	0	8710	16303	18283	122.147	1081	6598	7626	15305
	4M	33610	139.656	14878	0	16790	31668	35336	240.622	2109	12866	14813	29788
LU	64	3665	4.571	2081	0	540	2621	2639	4.267	289	1792	427	2508
	128	7307	9.352	8257	0	1106	9363	5237	12.506	1089	7168	875	9132
	256	14822	20.021	32769	0	2371	35140	12680	56.263	4113	28656	1889	34658
	512	29932	41.345	130945	0	4899	135844	40868	351.686	16353	114592	3903	134848
	1024	59921	83.993	523905	0	9956	533861	196488	2597.700	65601	458304	7931	531836

5.3 Page Fault Analysis

The number of page faults is also useful in explaining the performance improvement of JUMP. In software DSM, there are 3 types of page faults as described below:

- *PF1*: Page faults that can be served by the local processor, which is the home of the

page. They arise due to violation of access permission.

- *PF2*: Page faults that can be served by the local processor which is not the home of the page, but has cached a clean copy of that page to serve the fault.
- *PF3*: Page faults that have to be served by the remote processor.

Among the three types of page faults, serving *PF3* is time consuming, as it involves a pair of messages sending between two processors to serve the page fault. However, serving a *PF2* type fault can be more time-consuming than PF3 in some cases. This is because the page may be in the disk cache, and it costs a long time to bring the page from the disk back to the physical memory. Moreover, since the home is not local, the processor making the page fault must send a diff to the home of the page at synchronization time. The diff and the diff grant messages increases the cost of *PF2* faults. To improve the performance of DSM, minimizing the number of *PF2* faults is equally important as that for *PF3* faults.

Table 3 shows the number of each type of page faults occurred in the testing applications under JUMP and JIAJIA. Applications under JUMP produce 6-7% more page faults than JIAJIA. However, JUMP can convert most of the *PF2* faults in JIAJIA to *PF1* faults. As the number of *PF2* faults in JIAJIA accounts for 33-86% of the total number of page faults for the benchmark applications, JUMP reduces the need to send lengthy diffs significantly. Thus it improves the overall timing performance.

6 Conclusion

The protocol used in implementing a memory consistency model is as important as the model itself. It has a vital effect on the overall DSM performance. The JIAJIA system uses a fixed-home protocol to implement scope consistency. Although it is more efficient than TreadMark's homeless protocol, the concept of a fixed home for each memory page does not adapt well to the access patterns of applications. This paper discussed the new idea of a migrating-home protocol. In the protocol, the home of each page can be migrated to another processor when it accesses the page. We show that the migrating-home protocol reduces the number of bytes sent in the cluster. It also saves time in serving page faults by sending less diffs. The migrating-home protocol therefore improves the execution time of DSM applications substantially.

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