Fast User-Level Inter-thread Communication, Synchronisation

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Abstract

This project concerns the design and implementation of user-level inter-thread synchronisation and communication algorithms. A number of these algorithms have been implemented on the SMASH user-level thread scheduler for symmetric multiprocessors and multicore processors. All inter-thread communication primitives considered have two implementations: the lock-based implementation and the lock-free implementation. The performance of concurrent programs using these user-level primitives are measured and analyzed against the performance of programs using kernel-level inter-thread communication primitives. Besides, the differences between the lock-based implementations and lock-free implementations are also analyzed.

Index Terms

Lock-free, multithreading, synchronisation

1. Introduction

SMASH[4] is a user-level thread system running on Linux. It was originally developed by Kurt Debattista in 2001. Since then it has been actively developed in the University of Malta. Before this project, it lacked user level inter-thread communication primitives such as mutexes[8], semaphores[8], etc. As a result, whenever these primitives are needed, one has to use the one offered by the kernel. This may lead to some performance degradation. Because first since these primitives are implemented in the kernel, the operations on them usually involve system calls which are expensive. More importantly, if a user-level thread has to block on a primitive, the underlying kernel thread is also blocked, hence no other user-level threads can run on that kernel thread. We try to solve these problems by implementing inter-thread communication primitives at user level.

The main objective of this project is to implement a inter-thread communication library for a particular implementation of SMASH, and to find out how these primitives affect the performance of the SMASH system. Since these primitives are shared objects among threads, to guarantee the consistency of these objects, certain synchronization mechanisms have to be used. When implementing these synchronization algorithms, there are two approaches: the lock-based approach and the lock-free approach. In lock-based algorithms, critical sections are protected by some forms of locks. A typical example is the spin lock, which is widely used on SMP systems[8]. In this project, all lock-based designs use spin locks.

Usually, lock-based algorithms are easy to design. However, lock-based algorithms have problems like dead (or live) lock, priority inversion and the convoy effect. These problems can be solved with lock-free algorithms[9]. A concurrent algorithm is lock-free if after a finite number of execution steps, at least one of the participating threads progresses to the final goal. Lock-free algorithms are free of dead locks, but some particular threads may be delayed indefinitely. A stronger concept is the wait-free algorithms. An algorithm is wait-free if after a finite number of steps, all participating threads can finish. In this project, each inter-thread communication construct has a lock-free implementation.

2. Design and implementation

All communication primitives introduced in this project have their lock-based implementations in which critical sections are protected by spin locks. These lock-based implementations are very simple, hence we will not discuss their details. In contrast, their lock-free designs are complicated. Therefore in this paper, we mainly focus on them. In addition, we implemented a wait-free CSP communication channel[6] designed by Vella[3].

2.1. Lock-free Mutex

Algorithm 1 Lock free Mutex

```
L1  struct lockfree_mutex {
L2    int lock;
L3    int counter;
L4    struct fifo waiting_queue;
}

L5  FetchAndAdd(&mutex->counter,1);
L6    if(Swap(&mutex->lock,LOCKED))
L7      FetchAndAdd(&mutex->counter,-1);
L8    else {
L9      enqueue(thread_self,mutex->waiting_queue);
L10     schedule the next runnable thread;
L11   }

L12 counter = mutex->counter;
L13   if(counter == 0)
L14     if(!CAS2(<&mutex->lock,&mutex->counter>,
                 <0,0>,<1,0>)) {
L15       do {
L16         thread = dequeue(mutex->waiting_queue);
L17       }while(thread == NULL);
L18       FetchAndAdd(&mutex->counter, -1);
L19       enqueue(thread,run_queue);
L20     }
```

We designed a lock-free mutex in this project. The challenges in the design are how to modify the status of the mutex and manipulate the waiting queue concurrently in a lock-free manner. In addition, the lost-wake-up problem has to be solved. The instruction *Swap* was used to modify the *lock* field in the mutex. The waiting queue was adopted from [1]. In order to solve the lost-wake-up problem[8], we added to the mutex structure a field *counter* which represents the number of threads trying to acquire the mutex. When a thread calls Getmutex function, it first increments the counter by 1 with the atomic instruction *Fetch_And_Add*. Then it tries to obtain the mutex with *Swap*, if successful, the

Algorithm 2 The lock-free semaphore

```
L1  struct sem_t {
L2    int counter;
L3    struct fifo waiting_queue;
L4  }

L5  wait(sem_t s) {
L6    /* we may also use FetchAndAdd here, but I suspect
that the following code can improve the latency. */
L7    do {
L8      counter = s->counter;
L9    }while(!cas(&s->counter,counter,counter-1));
L10   if(counter < 0)
L11     save the current contex;
L12     enqueue(thread_self, s->waiting_queue);
L13     switch to the next runnable thread;
L14   else
L15     return
L16 }

L17 signal(sem_t s) {
L18   do{
L19     old = s->counter
L20     do{
L21       if( s->counter< 0 )
L22         tmp_thread = dequeue(s->waiting_queue);
L23         if(tmp_thread == NULL)
L24           continue;
L25         else
L26           FetchAndAdd(&s->counter, 1);
L27           wakeup(tmp_thread);
L28           return;
L29       else
L30         break;
L31     }while(true);
L32   }while(!CAS(&s->counter,old,old+1))
L33 }
```

counter is decremented by 1 with *Fetch_And_Add* again. Otherwise, the thread blocks on the mutex by inserting itself to the waiting queue. When a thread calls Releasemutex function, it checks whether the counter is zero, if so, then the lock field is set to zero, i.e. the mutex is released. This process is done with *CAS2* to guarantee the atomicity. *CAS2* fails to release the mutex iff the counter is non-zero which means there exists threads trying to obtain the mutex, but they may have or have not inserted themselves into the waiting queue. Hence, we used an indefinite loop to dequeue a thread from the waiting queue. The loop terminates if a thread has been successfully dequeued from the waiting queue. And finally the dequeued thread is woken up by being inserted into the run queue.

2.2. Lock-free semaphores

In the design of our lock-free semaphore, the waiting queue is the same lock-free FIFO queue as the one used our lock-free mutex. the counter is modified with *Compare_and_Swap* and is allowed to take negative value. If the counter is negative, then its modules represents the number of threads that are currently waiting for the semaphore, but some of them may not have inserted themselves into the waiting queue. When a thread tries to release a semaphore, it first reads the counter. If the counter is negative, then it tries to dequeue a thread from the waiting queue. If it gets a thread successfully, then it wakes up that thread and increments the counter by 1 with *Fetch_And_Add*, after which the function returns directly avoiding the outer loop between L18 and L32. However, if it fails to get a waiting thread, then there are two possibilities: the waiting thread has not inserted itself into the waiting queue, or the waiting has been emptied by other threads releasing the semaphore. Therefore, in the loop between L20 to L31, before the dequeue operation, the counter is checked first. If it is not negative any more, then the loop is broken out. In the otter loop, the counter is updated with *Compare_and_Swap*. This guarantees that after the inner loop is broken out, the counter has not been changed by any other threads, hence the semaphore can be released safely without the lost-wake-up problem.

2.3. Lock-free message queue

The message queues we implemented are unbounded, multiple sender, single receiver queues. Unboundedness means that these queues are potentially capable of storing infinitely many messages. The only limit is the memory space. Also there can be more than one sender that sends messages to the queue concurrently, but there is only one receiver. If the receiver tries to retrieve a message from a empty queue, it blocks until a sender wakes it up.

In order to implement the lock-free message queue, we use the lock-free queue from [1] to store messages and add a field *waiting_mark* to the queue structure. When a thread tries to fetch a message from the queue, it first sets the *waiting_mark* to WAITING to denote that the receiver is fetching messages. Then it performs the dequeue operation. If no message is found, then it blocks on the queue. When a sender sends a message, it inserts the message into the queue, then check the *waiting_mark*. If its value is WAITING, then the sender swaps NULL to the field *waiting_thread*. If the obtained value is not NULL which means that the receiver is blocking on the queue. Therefore the sender inserts the waiting thread into the run queue. Finally, the field *waiting_mark* is set to NOWAITING. Otherwise, the sender repeats the above process until the value of *waiting_mark* is NOWAITING.

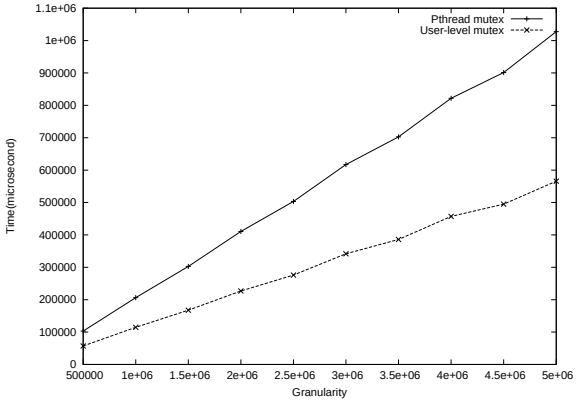
Algorithm 3 the lock-free message queue

```
struct message_queue {
  struct lockfree_fifo * queue;
  cthread * waiting_thread;
  int waiting_mark;
}

Fetch_message(struct message_queue * q) {
  while(true) {
    queue->waiting_mark = WAITING;
    result = dequeue(q->queue);
    if(result == NULL)
      save the current context;
      q->waiting_thread = thread_self;
      switch to the next runnable thread;
      continue on wakeup
    else
      queue->waiting_mark = NOWAITING;
      reture result;
}

Send_message(message, struct message_queue q) {
  enqueue(message, q->queue);
  do {
   thread = swap(&queue->waiting_thread,NULL);
   if(thread != NULL)
     queue->waiting_mark = NOWAITING;
     wakeup(thread);
  while(queue->waiting_mark == WAITING);
}
```

2.4. Wait-free channels

In this project, we also implemented Vella's wait-free CSP channel[3]. It was designed for KRoC which is an implementation for the OCCAM 2 programming language. The design was totally wait-free, it did not contain any form of locks or indefinite loops. In the design, the only special atomic instruction used was *Swap*. For details of the design, one can refer to [3].

Figure 1. Benchmarks of the system when using different mutexes



3. Results

The machine we used to conduct the benchmarks is a laptop equipped with a Intel Core2 Duo 1.83Ghz CPU with 4Mb L2 cache, 2Gb memory. The operating system is Debian GNU/Linux unstable with Linux kernel version 2.6.24. The compiler is GCC 4.3. When measuring these benchmarks, we try to run as few programs as possible, the largest program running being the X-window system.

3.1. Mutexes

We created six identical independent tasks, each of which contains nothing but a critical section protected by a mutex. In the critical section, a thread loops to increment a counter which is not shared. For each critical section, we create ten user-level threads working on it. The program loops for a number which is defined by GRANULARITY. We used a pthread mutex and our lock-free mutex to analyze the performance. It is desirable that the choice of different implementations of user-level mutexes will not make a significant difference since we are measuring the performance of the entire system, not that of mutexes.

From the results, we can see that on average, the performance of the system when using the user-level mutex is twice that when using pthread's mutex. This is because user-level mutexes never block the kernel threads. In fact, in the best case, it is possible that when using pthread's mutex, each kernel picks up a different task to do, therefore, there is no contention on these mutexes. In this case, we can still get the same performance as with user-level mutexes. However, in the worst case these tasks will be processed one by one in a strictly sequential manner, i.e. we do not benefit from the other CPU at all. This happens when the two kernel threads always try to work on the same task, so one of them is always blocked.

Another benchmark is to measure the performance of the function *Getmutex* and *Releasemutex* when the mutex is not under contention. In this case, it is not enough to time a single function call to *Getmutex* since the time of executing the function is not large enough to compensate the time that is cost by calling the function *gettimeofday()*[5]. In order to measure the benchmark accurately, we have to perform a large number of function call to *Getmutex*, then calculate the average time for a single call. However, this approach is not valid, because once we call *Getmutex*, it will lock the mutex. Hence, we call *Getmutex* followed by a call to *Releasemutex*, and we use a loop with 1000000 iterations to execute such a pair, and then calculate the average time for a single pair.

Table 1. Benchmark for mutexes(*ns*)

Pthread mutex	Lock-based	Lock-free
74	95	127

As we can see, the lock-free mutex is slower than the lock-based mutex for the case in which there is no contention, this is reasonable because the lock-free mutex uses a lot of expensive atomic operations like *Fetch_And_Add*, *Compare_And_Swap* and *Double_Compare_And_Swap*. In addition, the algorithm is also more complicated, while in contrast, the lock-based mutex just uses *Swap* and is therefore simpler. The pthread mutex is the fastest for the uncontended case, because Linux 2.6 series kernels features a new technique called futex[2], [7] (fast user space mutex). Prior to Linux 2.6, a call to *pthread_mutex_lock* had to enter the kernel and operate on the pthread mutex, then return to user mode even the mutex is not under contention. But by using futexes, all operation will remain in user mode for uncontended case and the pthread mutex on SMP system is also implemented though spin locks. The code is written directly assembly language and it is manually optimized, that is why it is the fastest.

3.2. Semaphores

Table 2. Benchmarks of semaphores(*ns*)

Lock-free	Lock-based	System
90	96	383

We use the same algorithm as the one used in the above section to measure the impact of user-level semaphores to the performance of the SMASH system, the only thing changed is that in this case we use semaphores initialized to some number to protect the critical section.

Due to the hardware limit, we are not able to measure the benchmark for a semaphore whose counter was initialized larger than one, because we only have a dual core machine, hence SMASH will only create two kernel threads and all user-level threads are run by these two kernel threads. So if a semaphore is initialized to a number larger than 1, there will not be any contention on the semaphore. As a result, we only conducted the benchmark with semaphores initialized with 1, but in this case, the semaphores behave just as mutexes, hence we have similar result patterns as above.

In fact, on the SMASH system, no matter how many user-level threads access a semaphore, if the semaphore is initialized to a number smaller than the number of CPUs (i.e. the number of kernel threads), then there will not be any contention on it since the number of threads accessing the semaphore concurrently is always smaller than the initial number of the semaphore's counter. However, our design is not limited to SMASH, it can be used in other contexts, and we do expect that in a system with a large set of CPUs, our lock-free design will perform better than the lock-based one because it reduces the memory contention. Even on a uniprocessor system, to implement a kind of system semaphore for kernel threads like pthreads on Linux, our design may also be a better solution than simply disabling the interrupts when a kernel thread accesses a semaphore, because disabling interrupts is also very expensive on uniprocessor systems.

In addition, we used the same mechanism in the previous section to conduct the benchmarks of the lock-free, lock-based semaphores and the system semaphore.From the result, we can see the lock-free implementation slightly outperformed the lock-based implementation and the system semaphore is the slowest. This is because operations on system semaphores are done by using system calls which are expensive.

3.3. Message queues

In this section, we are going to measure and compare the performance on the lock-based and lock-free message queues. We conducted the benchmarks for sending messages and for receiving messages. To conduct the former one, we created 25000 user-level threads, each of which sends a message to the message queue. To conduct the latter, we use a thread to dequeue a large number of messages which are preenqueued into the message queue, hence in this case the thread receiving messages never blocks. Finally, the average time of a signal operation is calculated

Table 3. Results of message queues(*ns*)

Enqueue operation	
Lock-based	Lock-free
1321	1257
Dequeue operation	
Lock-based	Lock-free
133	135

From the result, we can see that the difference between the lock-based approach and the lock-free approach is not significant for both sending messages and receiving messages. In fact, the dominating factor for the performance of our message queues is the performance of the FIFO queues used to store messages. Although according to [1], the lock-free FIFO queue we used is much faster than the FIFO queue with spin locks when a large number of threads access the queue concurrently. In our case, since we have only two kernel threads running concurrently when sending messages, and only one thread is running when receiving messages (in which case, there is no contention at all), it is not surprising that these two queues give similar performance. Another thing to note is from the result is that sending a message is much more expensive than dequeuing a message from the queue. However, this is not accurate, because when we were conducting the benchmark for sending messages, we timed both the message sending operations in each user-level thread, and the operation that the main thread of SMASH joins these 25000 user-level threads

and the thread scheduling operations, which are quite expensive. On the other hand, when we conducted the benchmark for the receiving operation, we only timed the dequeuing operation.

4. Conclusion

We implemented several user-level inter-thread communication primitives for SMASH, and gained some improvements to the overall performance of the SMASH system. Additionally, we also exploited lock-free algorithms by implementing the primitives we introduced in a lock-free manner. Although due to the limitation of the hardware we currently have, the advantage of these lock-free implementations can not be shown, we still believe that lock-free algorithms perform better than lock-based algorithms when a multiprocessor system is under high contention.

References

[1] Dominique Fober, Yann Qrlarey, Stephane Letz. Lock Free Techniques for Concurrent Access to Shared Objects. Technical report. GRAME - Computer Music Research Lab. 2001.

[2] Hubertus Franke and Rusty Russell. Fuss, Futexes and Furwocks: Fast Userlevel Locking in Linux. Ottawa Linux Symposium. 2002.

[3] Kevin Vella. Seamless parallel computing on heterogeneous networks of mutiprocessor workstations. PhD thesis, University of Kent at Canterbury, 1998.

[4] Kurt Debattista, High Performance Thread Scheduling on Share Memory Multiprocessors. Master's thesis, University of Malta, 2001.

[5] Marc J. Rochkind, Advanced UNIX Programming. Second Edition. ISBN 7-302-12645-3. 2004

[6] SGS-THOMSON Microelectronics Limited, Occam 2.1 Reference Manual, 1995.

[7] Ulrich Drepper, Futexes Are Tricky. Red Hat, Inc. 2008.

[8] Uresh Vahalia, Unix Internals: The New Frontiers. Prentice Hall. ISBN 0-13-101908-2. 1995.

[9] John D. Valois, Lock-free Data Structures. PhD thesis, Rensselaer Polytechnic Institute, Troy, New York, USA, 1995.