Minimizing Synchronization in Parallel Nested Loops

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ABSTRACT

Although, computer system architecture and the throughput enhances continuously, the need for high computational speed and power in many scientific applications grows every day. As a result, implementation of parallel applications has gained more attention. Since nested loops are the most time-consuming parts of most programs, we propose a method for scheduling uniform nested loops to processors based on the equation of a straight line which includes the maximum possible number of dependence vectors. Experimental results show that the proposed method imposes a lower communication between processors compared with similar methods.

Keywords: Uniform Nested loops, Scheduling, Chaining, Communication.

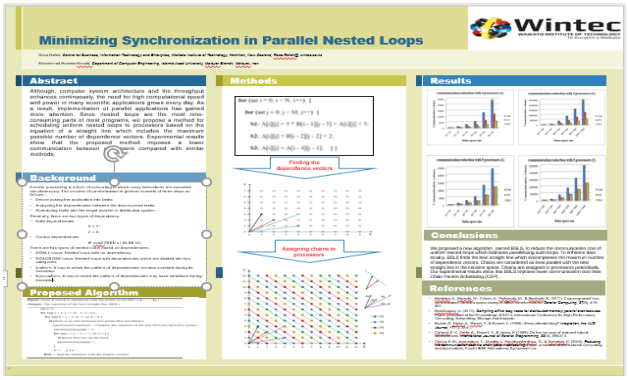
1. INTRODUCTION

Parallel processing is a form of computing in which many instructions are executed simultaneously. The process of parallelization in general consists of three steps as follows (Sinnen, 2007):

- Decomposing the application into tasks.
- Analysing the dependencies between the decomposed tasks.
- Scheduling tasks into the target parallel or distributed system.

Since the most time-consuming parts of scientific and engineering sequential programs are nested loops and recursive procedures, their optimization plays an important role in reducing the execution time of the program. For parallelizing nested loops, at first, the iterations should be broken down into tasks. In the second step, dependencies between tasks must be discovered. Dependencies prevent parallel execution of tasks efficiently. Generally, there are two types of dependencies:

- Data dependencies caused by data transfer between tasks. For example.: X = Y ; Z = X;



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- Control dependencies caused by the order of instructions that are logically related to each other. For example:

IF cond THEN s1 ELSE s2

There are two types of nested loops based on dependencies:

- DOALL loops: Nested loops with no dependency.
- DOACROSS loops: Nested loops with dependencies which are divided into two categories:
  - Uniform: A loop in which the pattern of dependencies remains constant during its execution
  - Non-uniform. A loop in which the pattern of dependencies may have variations during execution.

In this paper we propose a novel approach to reduce the communication in uniform nested loops.

2. METHODOLOGY

Loop iteration space: Iteration space of any n-dimensional nested loop can be mapped into a finite discrete n-dimensional Cartesian space $J=\{(j1,\ldots,jn) \in Nn \mid lr \leq jr \leq ur , 1 \leq r \leq n\}$, in which each point represents an iteration of the nested loop. The body of each loop may include a set of instructions.

Loop dependencies: Statements S1 in iteration J1 is dependent to statement S2 in iteration J2 if and only the following conditions hold:

1- (J1 < J2) or (J1 = J2) and an execution path exists from J1 to J2

2- both statements access a same memory location

3- at least one access modifies the memory content

Dependence vectors: In a n-dimensional nested loop existing dependency between two iterations J1 and J2 (if any) is represented by a dependence vector d of length n:

d(J1 , J2) = (J21 – J11 , J22 – J12 ,…, J2n – J1n)

The size of dependence vector, which is always greater than zero, shows the number of iterations between two dependent iterations. If the size of all dependence vectors remains fixed during the execution of a loop, the loop is known as a uniform loop.

Example 1: The dependence vectors of the two dimensional nested loop in Figure 1are: d1 = (1, 3), d2 = (2, 2), d3 = (4, 1) and are shown in Figure 2.

```
for (int i = 0; i < N; i++)  {
  for (int j = 0; j < M; j++)  {
    S1: A[i][j] = 5 * B[i - 1][j - 3] + A[i][j] + 3;
    S2: A[i][j] = B[i - 2][j - 2] + 2;
    S3: A[i][j] = A[i - 4][j - 1];   } }
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Figure 1. A two Dimensional nested loop with three dependence vectors

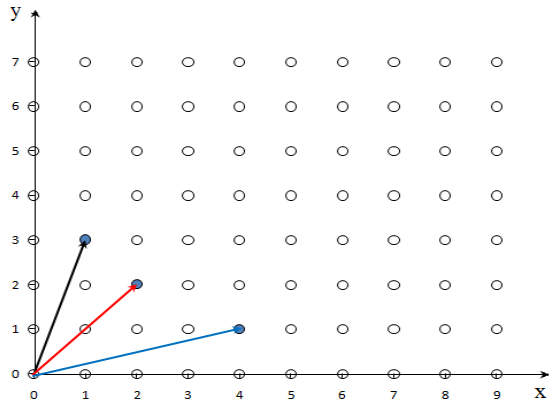

Figure 2. Dependence vectors of nested loops in Figure 1

The communication vector (dc): Communication vector is a vector that incurs the largest amount of communication. In most cases the communication vector is the dependence vector with the smallest absolute coordinate values.

Our proposed algorithm which is referred as the Best Straight Line Scheduling (BSLS), uses the concept of chains which was introduced in Chain Pattern Scheduling (CPS) algorithm. The idea of BSLS is to minimize the communication cost between dependent iterations by assigning them to a single processor. In other words, when a point Js= (xs , ys) sends data to points in set DP={ J1,. . . , Jm } because of dependence vectors d1, . . . , dm, by mapping Js and all points of set DP to a single processor, the communication incurred by vectors d1, . . . , dm is eliminated. However it is impossible to map all such points to a processor. If we map the point Js, with maximum number of possible points from DP to a processor, the data locality will be increased. In the proposed approach, the points assigned to a processor are determined by a straight line which passes through the maximum number of points in DP. This line is referred to as the best straight line.

In this algorithm, for each pair of points in DP, the equation of the line passes these two points is determined. Then, the number of other points lie on this line is calculated. The line on which the maximum number of points lies will be the best straight line. The points of DP lie on the best straight line along with Js are assigned to a single processor.

Since the dependence vectors remain unchanged during the execution of the loop, the equation of the straight line can be used to chain all points in the iteration space. In a two-dimensional space, assuming the equation of the straight line be y=m∗x+r, the equation of chains are are: C_i = { j ∈ J | j = m ∗ x + r_i , m and r ∈ R} where r_i is the offset of the *i*th chain with the best straight line.

Example 2: We consider a system with 4 processor and a two-dimensional uniform nested loop with the following dependence vectors: d_1 = (1, 3), d_2 = (2, 2), d_3 = (4, 1) and the communication vector d_c = d_2. The following equations are candidates for being the equation of the best straight line:

1) y = - x + 4 { (1,3) , (2,2) }
2) y = - 2/3 x + 8 { (1,3) , (4,1) }
3) y = - 1/2 x + 9 { (2,2) , (4,1) }

Each line passes two points of set DP, thus, each of them can only eliminate two dependence vectors. In Figure 3 the equation y = -x + 4 is being considered for the best straight line and chains are formed in parallel with this line. In this way, the communication cost between d_1 and d_2 is eliminated. Chains are assigned to processors in a round robin fashion shown in the figure in different colors.

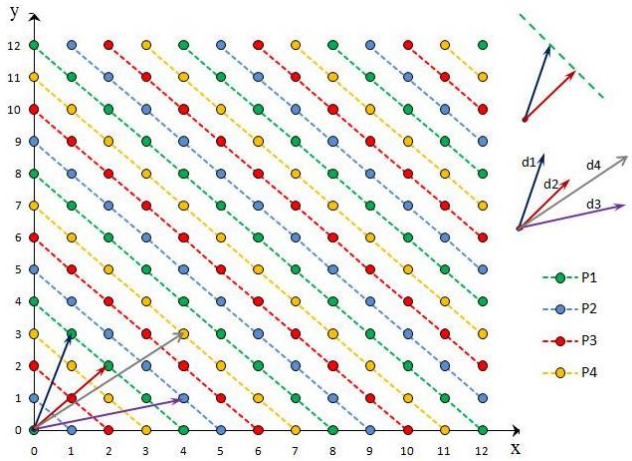

Figure 3. Chaining of points in an index space of a two dimensional nested loop with four dependence vectors and four processors using the proposed algorithm

3. RESULTS

To evaluate the proposed approach in terms of the communication cost, we compare it with CSP. In this experiment, we examine the uniform nested loop given in Example 1which includes four dependence vectors. The index space ranges from 10 × 10 to 1000 × 1000. Results have been depicted in Figures 4 and 5 with 4 and 5 processors, respectively. Since in this experiment each line passes two points (see Example 5), the worst case of the proposed algorithm happens. However, the proposed algorithm works better than CSP when number of processors is 4. Note that in diagrams, the *total* column shows all dependencies in the iteration space.

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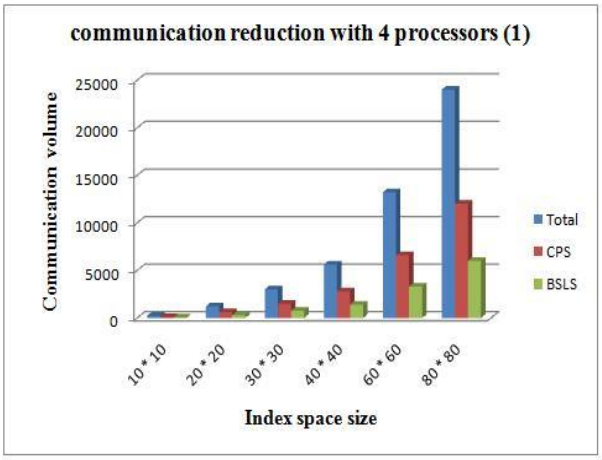


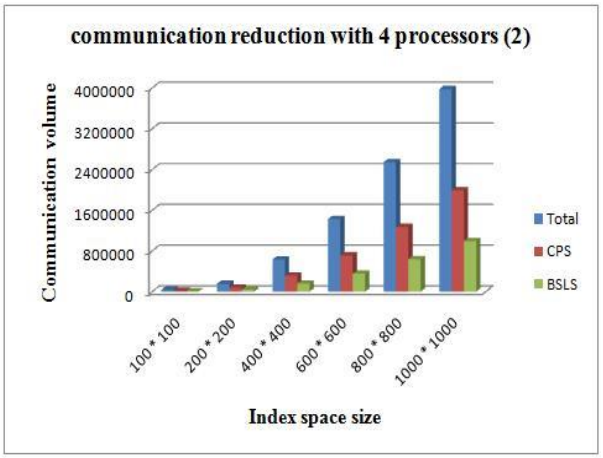
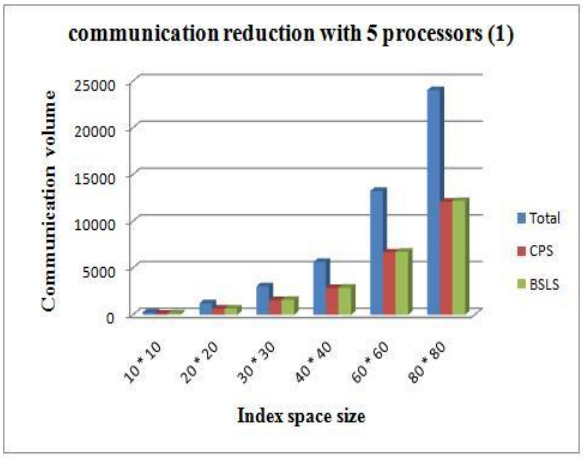


Figure 4. Experimental results, BSLS versus CPS, on four processors



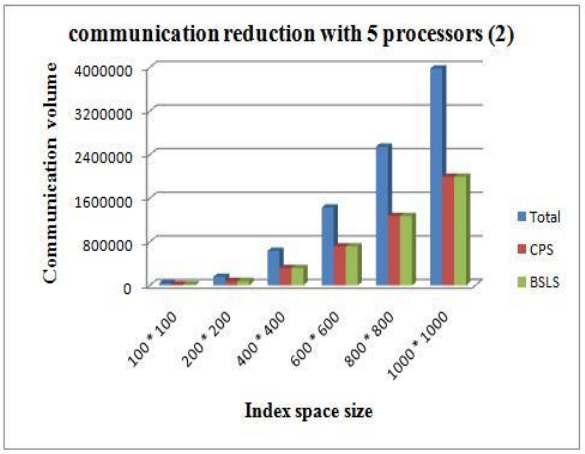


Figure 5. Experimental results, BSLS versus CPS, on five processors