

# Communication and Topology-aware Load Balancing in Charm++ with TreeMatch

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**Abstract**—Programming multicore or manycore architectures is a hard challenge particularly if one wants to fully take advantage of their computing power. Moreover, a hierarchical topology implies that communication performance is heterogeneous and this characteristic should also be exploited. We developed two load balancers for Charm++ that take into account both aspects depending on the fact that the application is compute-bound or communication-bound. This work is based on our TREEMATCH library that compute process placement in order to reduce an application communication cost based on the hardware topology. We show that the proposed load-balancing scheme manages to improve the execution times for the two classes of parallel applications.

## I. INTRODUCTION

Simulation is now wide-spread in the fields of science and technology, because actual experimentation, even when possible at all, is becoming increasingly costly both in terms of time and resources. This simulation step itself is often conducted as a scientific application executed on a dedicated computer. Moreover, since these simulations are expected to be more and more refined and precise and to deal sometimes with very large time scales, the required computing power is therefore huge. As a consequence, delivering this computing power to the scientific applications is a challenge that needs to be addressed.

From a hardware perspective, a single type of computers is able to deliver the required computing power: parallel computers. However, programming a parallel architecture is not a trivial undertaking because of the intrinsic concurrency of these machines and of the multiplicity of the computing nodes and cores present. As a consequence, dedicated paradigms, tools and environments have to be used to ease the task of developing parallel applications.

Structuring the application and exposing its parallelism as much as possible is an efficient solution advocated by several programming environments such as Cilk [1] or Charm++ [2] [3] for instance. Such environments rely on fine grain parallelism and create software computing entities that usually outnumber the physical computing units available in the parallel architecture. This induces execution issues that have to be handled by the environment’s runtime system. For instance, the workload can be very different from one core to the other, resulting in a global imbalance that may harm the application’s performance. As a consequence, load balancing schemes are usually proposed in these environments

and improve the performance by optimizing the use of the available resources.

However, load balancing schemes fail to grasp an important aspect of today’s parallel computers: their hierarchical and heterogeneous nature, communication wise. Indeed, since the advent of multicore/manycore CPUs, organization of the memory banks as well as the presence of several cache levels lead to non-uniform memory access times. That is, the time to access or move data depends on the physical location of the process inside of the computing node. Moreover, a good load balancing scheme does not always guarantee that the communication in the application will be optimized as well. As a consequence, load balancing schemes can be enhanced in order to take into consideration not only the load of the various cores, but also the amount of communication between the process executing the various tasks of the parallel application. This can be achieved by matching the communication pattern of the application to the underlying hardware.

Therefore, the various application processes have to be placed carefully on the various cores/CPU’s of the machine. This technique can improve application performance and ultimately, scalability since communication costs are decreased. So far, a compelling idea is to try and regroup on the same computing node the processes sharing the most data so as to reduce the application communication costs [4], [5]. However it now becomes necessary to push further this idea and apply it to the subsets of application processes *within* a computing node to take advantage of the complex structure of its memory.

In previous works [6], we proposed a library called TREEMATCH that computes a relevant process placement and that targets clusters of multicore NUMA nodes. Since TREEMATCH yields promising results for message-passing based applications [7] on such targets, we believe that it could benefit to other programming models, and in particular the fine grain ones, by enhancing their load balancing schemes so as to better take advantage of clusters of NUMA multicore nodes. In this paper, we extend this library to deal with constraint placement and we study the results achieved by two new topology-aware load-balancers for applications developed with the Charm++ framework. The choice of the load-balancer depends on the class of the application: compute-bound or communication bound. By introducing TREEMATCH in the load balancing schemes of Charm++, we managed to outperform some other communication-aware schemes available.

This paper is organized as follows: Section II exposes the

motivation and context of the work while Section III lists various related works. The TREEMATCH algorithm is described in Section IV and its integration in the load-balancing scheme of Charm++ is described in Section V. The results achieved are detailed in Section VI while Section VII concludes this paper.

## II. MOTIVATIONS AND CONTEXT

As discussed in the introduction, scientific applications that are in need of a massive computing power rely on parallel computer since they are the only architectures able to deliver the requested resources. However, a gap remains between the performance achieved at the application level and the performance of the underlying hardware. This issue can be addressed in several ways: first, using an appropriate programming model can help to improve the overall performance of the target application. Indeed, according to the application structure and its degree of parallelism, different programming models or frameworks might be more efficient. For instance, coarse grain applications with explicit communications are likely to use an interface such as the Message Passing Interface (MPI), while finer grain ones without explicit communications are likely to employ a standard such as OpenMP for instance. The target architecture is also a determinant factor in the choice of the programming tools. For instance, for cluster-based architectures featuring an interconnection network, it is necessary to exchange messages between the nodes, thus a message-passing based paradigm is likely to be the best fit, while in the case of shared-memory machines, the range of choices is wider since models with implicit communications are also possible (e.g. PGAS, multithreading, etc.)<sup>1</sup>.

Second, it is necessary to use an optimized implementation of the chosen programming standard. This encompasses two distinct aspects: on one hand the implementation of the functions defined by the standard should obviously be the most efficient possible, on the other hand, the interactions of this implementation with the underlying target hardware should also be carefully defined and enforced. This is usually the role of the underlying runtime system (e.g. a process manager for an MPI implementation). This runtime system will also trigger mechanisms that can improve the overall performance of the application. A mechanism such as load balancing falls into this category. By dispatching the workload dynamically (as the application executes itself) on the various processors of the architecture, one can expect a decrease in execution times. However, most of load balancing schemes fail to fully take into account other factors that have an impact on application performance. Such factors include objects migration (when balancing the load, processing entities are likely to migrate from one core to another one) and communication costs for instance.

However, these communication costs are increasingly difficult to understand, because the current parallel architectures have undergone tremendous changes over the past few years. Indeed, the amount of computing cores available inside a node has increased dramatically. It is not uncommon to find machines featuring a dozen of cores per processor, and this number is expected to grow steadily in the forthcoming years.

<sup>1</sup>Our course, PGAS and OpenMP implementations for distributed memory do exist, but their runtime system rely on the message passing paradigm for their internode communications.

Moreover, this trend also impacts the memory organization and layout: memory banks are scattered throughout the node and the cache levels now form a complex, multi-level hierarchy. As a consequence, the communication costs within a single node are not homogeneous anymore. Practically speaking, these costs for exchanging data or messages between processes sharing the same node depend on their physical location (in the node). This is known as Non-Uniform Memory Access (NUMA) effects. An intuitive idea is therefore to place processes that communicate the most to processors/cores that are physically the closest to each other, because they share more cache levels and the NUMA effects are less prominent. Moreover, the increase of the memory resources does not follow the same trend as the number of processors. Indeed, the amount of memory available *per core* is expected to decrease. As a consequence, the issue of reducing the communication costs in a parallel application is going to become more and more crucial, even for compute-bound applications as the amount of communications in such applications is likely to increase due to the scarcity of the memory resources.

The underlying physical architecture has thus to be modeled in a convenient but realistic and usable fashion. One way is to assess the performance of the hardware with several benchmarks and to make use of these results to place the processes accordingly. This quantitative approach lacks dynamicity, requires to gather information prior to any application run and is prone to measurement errors. Another way to deal with this issue is to use a qualitative approach where hardware organization and structure shall guide the placement. The advantages of this approach are its flexibility since it does not rely on a prior gathering of information, its genericity and dynamicity, provided that a relevant tool is used to perform this step. Currently, such a standard tool does not exist, but one can nevertheless rely on a recent effort such as HWLOC [8] that is available for a substantial range of hardware.

To sum up, our approach is to consider additional factors when balancing the load for applications using a fine grain programming model. These factors include the migration costs and the communication costs between computing entities (e.g. tasks, processes, objects, threads). As for the communication costs, we decrease them thanks to a qualitative model of the underlying hardware, which ensures dynamicity, flexibility and genericity.

## III. STATE OF THE ART

The issue of topology-aware mapping has been studied previously [5], [9]. In particular, MPI implementations allow to easily gather communication information such as the number of messages or the amount of data exchanged. Besides, some of these implementations feature means to bind processes on processing units in their runtime systems (e.g. process managers).

MPI 2.2 is a good example [10]. Beyond a static placement, some works focus on online placement by relying on a technique called *rank reordering* ([7], [4]). Finally, Dummler [11] explored the issue of hybrid, MPI + OpenMP application multithreaded process mapping. TREEMATCH [6] is an algorithm which takes an application's communication pattern as input and the target machines's architecture to compute a relevant process placement.

Charm++ [2], [12] is a message passing-based programming environment based on the C++ language. However, while MPI considers processes in its programming model (with a granularity that is most of the time coarse), Charm++ model is based on a finer granularity by splitting computation in smaller tasks called *chares*. These chares are characterized by their CPU load, their input and output communication and some other useful fields. This makes it easier to introduce load balancing mechanisms. A strong advantage of Charm++ is therefore the possibility to design, plug and test load-balancers transparently without changing the application code. Moreover, several applications have been developed using Charm++ in different scientific topics. For instance, it is the case of NAMD [13] and LeanMD [14] (molecular dynamic applications), or ChaNGa [15] (cosmological computations).

Common load balancing schemes, which take into account the CPU load on each processing unit, have been extended in some works to take into account the topology of the underlying architectures. In a previous work, Bhatel  & Kal  [16] presented the benefits of topology aware mapping on a torus topology. NucoLB and HwTopoLB [17] [18] apply load balancing based on a quantitative approach of the topology links (latency and bandwidth figures are necessary). Besides, this kind of strategy requires to assess the target architecture communication performance with appropriate tools before running any application. Our solution based on TREEMATCH is fully dynamic because we use only a qualitative approach for our representation of the hardware topology.

#### IV. EXTENSION OF TREEMATCH TO ACCOUNT FOR PLACEMENT CONSTRAINTS

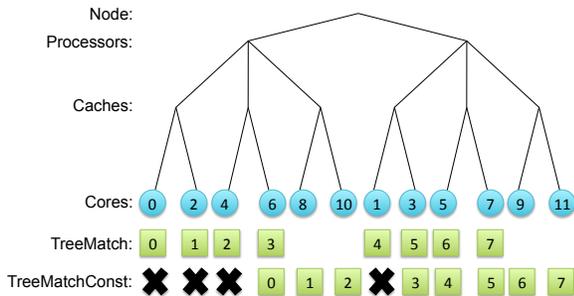


Fig. 1. A 2 : 3 : 2 topology tree modeling a node with two processors featuring 6 PUs/cores each, where two PUs/cores share a common cache. Note that the core numbering follows the physical one and not the logical one. Two results are displayed. The basic TREEMATCH one and the TREEMATCHCONST one with constraints on leaves/cores number 0, 2, 4 and 1 as in the example.

In this section, we present the process placement method based on our TREEMATCH solution. The aim of our work is to assign each process to its dedicated processing unit (usually a core) in order to reduce communication costs between processes. The core algorithm takes as input a matrix modeling the amount of communication between processes and a representation of the underlying hierarchical architecture modeled as a tree where the leaves represent the processing units (PUs) on which the processes should be mapped (see Fig. 1). TREEMATCH considers balanced trees, that is, trees in which the arity of the node at each level is the same. This enables the following compact notation of trees:  $a_1 : a_2 : \dots : a_n$  where

$n$  is the number of levels and  $a_i$  is the arity of all the nodes at level  $i$ . Therefore, the tree depicted in Fig. 1 is modeled with this notation as: 2 : 3 : 2. TREEMATCH relies on several algorithms. The first version was proposed in [6], [7]. In this earlier version, when the number of PUs is larger than the number of processes then, the user cannot specify which PUs cannot be used and the algorithm decides where to allocate the processes using only communication cost into account. However, such approach is suitable only in the case of shared-memory machines and when no load balancing is applied. In our case, we target clusters of multicore nodes addressing load-balancing issues. Moreover, if we consider eight processes to be mapped on the architecture modeled in Fig. 1, there is no guarantee that the earlier version of TREEMATCH would map the processes evenly. Indeed, as shown in Fig 1, leaves number 8, 10, 9 and 11 are not used. It is not possible to mark a given subset of leaves as unused. To ensure an allocation that comply to criteria of this type, we have designed an enhanced version of the algorithm that is now able to take into account *constraints* explicitly listing the PUs/leaves that cannot be used for the mapping. This new version is called TREEMATCHCONST to account for the constraints given by the user.

For instance, imagine that the user wants to prevent PUs/leaves number 0, 2, 4, and 11 to be used for some reason. We give this information as new input to the algorithm along with the topology description and the communication pattern as shown in Algorithm 1. For the sake of simplicity, we assume that the number of the constraints plus the dimension of the communication matrix is equal to the number of leaves of the tree. If this is not the case, the workaround consists of padding the required dimension and then, once the result is output, we simply ignore the mapping of the virtual processes corresponding to the padded values.

TREEMATCHCONST is a recursive algorithm. In our example, for the first call we have  $T$ , the tree depicted in Fig 1, the communication matrix displayed in Fig 2 and  $C = \{0, 4, 2, 1\}$ . Let  $k$  be the arity of tree  $T$  for the corresponding recursive step ( $k=2$  for the first recursive step). In line 2 of the algorithm, we  $k$ -partition the communication matrix but we take the constraints into account. As the constraints state that three leaves on the left subtree and one on the right subtree cannot be used, we need to partition the communication matrix such that exactly three processes are allocated on the left subtree and exactly five on the right one with the goal of minimizing the communication cost between each partition. Unfortunately, no graph partitioner is able to provide an unbalanced and exact partitioning at the same time. For instance, Scotch [19] provides only balanced partitioning while Metis [20] never guarantees that a given partition has the exact specified size. Therefore, we have implemented a simple, greedy, randomized  $k$ -partitioner for performing this task. As random, greedy  $k$ -partitioning does not necessary provide a very good solution, we call this part a thousand times and keep the best solution. In our example, the first three processes are mapped on the left subtree and the five last processes on the right one. We can then call recursively TREEMATCHCONST with new inputs on each subtree. For instance, in the left subtree we have only the communication matrix corresponding to the first three processes (as shown in Fig. 3), the tree  $T$  is the one starting at

Proc	0	1	2	3	4	5	6	7
0	0	1000	10	1	100	1	1	1
1	1000	0	1000	1	1	100	1	1
2	10	1000	0	1000	1	1	100	1
3	1	1	1000	0	1	1	1	100
4	100	1	1	1	0	1000	10	1
5	1	100	1	1	1000	0	1000	1
6	1	1	100	1	10	1000	0	1000
7	1	1	1	100	1	1	1000	0

Fig. 2. Communication matrix example

Proc	0	1	2
0	0	1000	10
1	1000	0	1000
2	10	1000	0

Fig. 3. Communication matrix of the left subtree after step 1

the *processors* level and is of arity  $k = 3$  and the constraints are  $C = 0, 4, 2$ . When the algorithm reaches the bottom of the tree the result can be aggregated. In our case, it is displayed by Fig. 1.

It is worth to note that regardless of the version of the algorithm used, TREEMATCH uses structural information (a topology tree) and never needs quantitative information about the underlying hardware (e.g. bus speed, network bandwidth, latencies, etc.) as opposed to other approaches such as NucolB [18] or Scotch [21]. We believe that this advocates for our approach, as dealing with qualitative and structural information does not require to assess the hardware performance and is therefore insensitive to incorrect or partial measures.

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### Algorithm 1: The TREEMATCHCONST Algorithm

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```

Input:  $T$  // The topology tree
Input:  $m$  // The communication matrix
Input:  $C$  // The constraints array
1  $k \leftarrow$  arity at the top of the tree  $T$ ;
2  $p \leftarrow$  constraint_k_partition( $k, m, C$ ); // find partitions of size  $k$ 
   taking the constraints into account
3  $tab\_m \leftarrow$  split_com_mat( $C, k, p$ ); // Split the communication
   matrix in  $k$  parts according to the partition just found
   above
4  $tab\_C \leftarrow$  split_constraints( $C, k, T$ ); // Construct a tab of
   constraints of size  $k$ : one for each partitions
5 if  $T$  is not a leaf then
   | // recursively call TREEMATCHCONST on the  $k$ 
   | subtrees of the root of  $T$ ;
6   foreach  $i$  in  $0..k - 1$  do
7     | execute TREEMATCHCONST on the  $i^{th}$  subtree of  $T$ ,  $tab\_m[i]$ ,
7     |  $tab\_C[i]$ .
8   |  $r \leftarrow$  aggregate results of each subtrees;
9 else
10  |  $r \leftarrow$  assign the process/constraint to  $T$ ;
11 return  $r$  as result for  $T$ ;

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## V. LOAD-BALANCING IN CHARM++ WITH TREEMATCH

Charm++ is a runtime system and a programming language implementing the message passing paradigm. Unlike MPI, Charm++ does not manipulate processes but independent computing objects called *chares*. These fine grain objects can be in higher numbers than the hardware processing units (e.g. CPUs, cores). Moreover, if this model is used jointly with a

dynamic load balancing system, it can easily level the CPU consumption and consequently improve the execution time of applications.

But while some applications are limited because of a huge imbalance (LeanMD [14] for example), some others feature chares which exchange lots of data (e.g. kNeighbor or Stencil3D). These different behaviors led us to create two distinct load balancers based on TREEMATCH. The first one, called TMLB\_MIN\_WEIGHT, applies a communication-aware load balancing scheme by favouring the CPU load balance. To do so, it solves a maximum weight matching problem in order to minimize chares migration. The second algorithm, designed for communication-bound applications and called TMLB\_TREEBASED, computes a placement of groups of chares on each processing unit. Then, it considers each node and enforces some load balancing while keeping as much balanced as possible the chare placement in order to minimize communication costs. We detail these two algorithms in the following two sections.

### A. Load balancing with communication and migration minimization

As explained previously, some applications are very unbalanced in terms of CPU load. However, such applications also exchange data. Our goal is to address both issues, that is load balancing improvement and communication costs decrease. That is why we designed an algorithm which carries out some load balancing while keeping as close as possible the communicating chares, taking into account the topology. However, if we only take into account both problems, results show marginal improvements. The reason comes from the chares migration. When we consider all chares and reorder them according to their communication exchanges or their load, the probability that a chare will stay on its original processing unit is poor. The goal is therefore threefold : to balance the load, to minimize communication costs and to minimize chares migration. We detail, in our algorithm, how we reduce these migrations by solving a maximum weight matching problem.

This first load balancing algorithm can be found on Algorithm 2. To explain it, we can consider an application which creates a hundred chares and will be executed on four cores. After a few iterations, Charm++ calls the load balancing algorithm. First, it extracts the chares communication pattern from the application monitor (provided by the Charm++ runtime). This results in a  $100 \times 100$  matrix. Then, we create a fake topology tree by decomposing the order of this matrix in prime factors. In our example, the topology tree will be:  $2 : 2 : 5 : 5$ . Then, we run TREEMATCH to find an appropriate chares permutation in order to have the most communicating chares as close as possible in the tree. Once we obtain this permutation, we split it in a number of parts equal to the number of cores (four in our case) of the underlying architecture. In this case, each part corresponds to the group of chares of each of the four subtrees of the second level of the fake topology. Then, we apply the AssignChareOnCore function as follows: we sort each part by decreasing load. Hence, each part corresponds to a core. The main loop first assigns each chare to its corresponding core by considering at each iteration the less loaded core and its most loaded chare.

When a core has received all the chares of its part but it is still the less loaded, we select chares from an other part. This algorithm keeps a lot of communicating chares together and applies load balancing using the less loaded ones. Therefore, we can make a fine CPU load balancing. Moreover, at each new chare assignement, we update a migration matrix such as we increment  $m\_mig[old\_core][new\_core]$  when the chare has to move from  $old\_core$  to  $new\_core$ .

At the end of this phase, we have as many groups of chares as we have cores. The remaining question is how to map this group of chares onto the physical cores. We solve this problem with the goal of minimizing the chares migration. Minimizing the migrations corresponds to solve a minimum weight matching problem on the migration matrix. Indeed, each entry  $m\_mig[i][j]$  gives the migration cost when allocating group  $i$  on core  $j$ . A minimum weight marching of this matrix is therefore an assignment of the groups to the cores such that the sum of migration costs is minimized. Finding such matching is done in polynomial time by the Hungarian algorithm [22]

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#### Algorithm 2: The TMLB\_MIN\_WEIGHT Algorithm

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Input:  $m\_chares$  The communication matrix between chares
Input:  $n$  Order of  $m\_chares$ 
Input:  $fake\_T$  A fake topology tree with  $n$  leaves
Input:  $m\_mig$  The migration matrix between cores
1 ;
2  $p \leftarrow$  Permutation( $m\_chares, fake\_T$ );
3 SortEachPartDesc( $p, nb\_cores$ )
4 foreach  $i$  in  $0..n$  do
5    $c \leftarrow$  LessLoadedCore();
6    $chare \leftarrow$  ChooseChare( $c$ );
7   AssignChareOnCore( $chare, c$ );
8   UpdateMigrationMatrix( $m\_mig, chare$ )
9
10  $h \leftarrow$  HungarianAlgorithm( $m\_mig$ );
11 foreach  $chare$  do
12   SetNewPe( $chare, h$ )

```

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#### B. Tree-based chares placement and load balancing

The algorithm of the previous section is designed for compute-bound applications. In this section, we tackle the issue of balancing the load for communication-bound applications. Here, the load balancer based on TREEMATCH first reduces communication costs while balancing the load on each processing unit. Our algorithm is presented on Algorithm 3.

For example, consider a 110 chares applications to be executed on two nodes, eight cores architecture (four cores per node). At the beginning of the execution, Charm++ groups these chares to the cores. At each load-balancing step, the first part of the algorithm consists in building the communication matrix of these groups of chares, gather the topology and apply TREEMATCH to permute these groups to the cores such that we minimize communication costs between cores. The second part of our algorithm goes up in the topology tree and considers the nodes (i.e. the set of cores that share the same memory banks). For each node in our architecture, we apply locally and in parallel a load-balancing algorithm. For example, assume that the first step assigns 55 chares to each node. This means that these 55 chares are grouped in 4 parts (one per core). In order to balance the load of these chares on each of the 4 cores, we have to create a

fake topology on which we will be able to bind the chares. Because of the grouping algorithm of TREEMATCH, we could fail to find a good placement if the prime factorization contains a large prime number. To avoid this problem, we use the new feature in TREEMATCHCONST: the possibility to put constraints on leaves in our topology. Thus, to create the needed fake topology, we take the number of chares to be bound and we increment this value to obtain a number for which the prime factorization will be only decomposed in 2 and 3. This increment will improve the ability of TREEMATCH to create groups and to find a good process placement. In our case, the increment leads to consider a topology of 64 leaves and the following binary tree:  $2 : 2 : 2 : 2 : 2 : 2$ . To map the 55 real chares to the 64 leaves of this tree and keep a good chares balance, we apply constraints regularly on each smallest subtree. These constraints will be given to the TREEMATCHCONST algorithm that is based on an unbalanced  $k$ -partitioning. Once we have a satisfactory chares permutation, we assign them on their new core. This is done using the same AssignChareOnCore method as in the previous algorithm.

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#### Algorithm 3: The TMLB\_TREEBASED Algorithm

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Input:  $m\_pu$  The communication matrix between Pe
Input:  $T$  The topology tree
2  $p \leftarrow$  Permutation( $m\_pu, T$ );
3 foreach  $chare$  do
4   SetNewPe( $chare, p$ )
5
6 foreach  $node$  in parallel do
   Input:  $m\_chares$  The communication matrix between
       chare in the current node
   Input:  $n$  Order of  $m\_chares$ 
    $fake\_T \leftarrow$  CreateFakeTopology();
    $p \leftarrow$  PermutationWithConstraints( $m\_chare, fake\_T$ );
7
8
9
10 foreach  $i$  in  $0..n$  do
11    $c \leftarrow$  LessLoadedCore();
12    $chare \leftarrow$  ChooseChare( $c$ );
13   AssignChareOnCore( $chare, c$ );

```

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## VI. EXPERIMENTAL RESULTS

In this section, we present the results obtained with our two load balancers. We selected three applications. The first one, called LeanMD [14], is a molecular dynamic application known to have a huge load imbalance. We did our tests for this application with TMLB\_MIN\_WEIGHT. The last two applications, kNeighbor (an iterative application where each chare communicates with  $k$  others) and Stencil3D (a three dimensional stencil application)<sup>2</sup> are known to exchange a lot of data. That is why we conducted the tests using the TMLB\_TREEBASED scheme. All experiments were carried out on 16 nodes of the PlaFRIM platform. The nodes are linked with an InfiniBand interconnect (HCA: Mellanox Technologies, MT26428 ConnectX IB QDR). Each node contains two Quad-core-INTEL XEON NEHALEM X5550 (2.66 GHz) processors. 8 Mbytes of L3 cache are shared between the four cores of a CPU. There are also 24 GB of 1.33GHz DDR3 RAM on each node. The operating system is a SUSE Linux (2.6.27 kernel). We used the repository version of Charm++ which was a 6.4.0 development version. Finally, for all these experiments, the metric accounting for chares/process affinity if the number of messages exchanged.

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<sup>2</sup>kNeighbor and Stencil3D are part of the Charm++ benchmarks suit

We compare our solutions on one hand with an execution without any load balancing (DummyLB or Baseline) and on the other hand with the standard load-balancers that are available by default in Charm++. These load balancers are greedy strategies or are the suggested ones for the application. Particularly, GreedyLB (resp. GreedyCommLB) uses load (resp. load and communication) to assign chares on cores with the following strategy: the highest loaded char is mapped on the less loaded core. RefineCommLB take objects from overloaded cores and assign them in order to reach an average load. RefineCommLB is one of the suggested strategy for KNeighbor. We did not compare our approach to NucoLB as it was designed for shared-memory machines.

### A. LeanMD

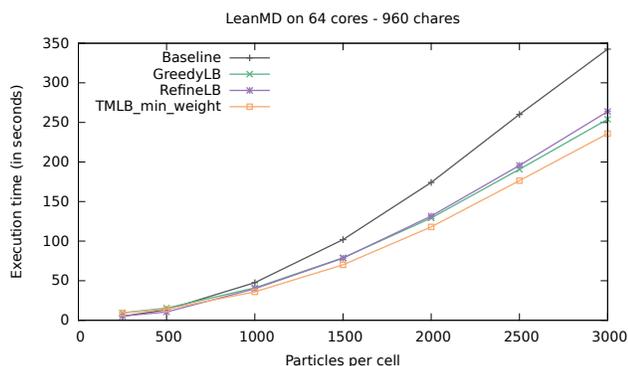


Fig. 4. Execution time (including load-balancing) vs. number of particles per cell of the LeanMD application on 64 cores for different load balancing strategies

LeanMD is a molecular dynamics application which is very unbalanced. Among others parameters, the number of particles per cell (per char in a software manner) can be modify in order to generate more computation and communication. We vary this value in our experiments. This application provides some communication flow but it is insignificant compared to the load imbalance. Our TMLB\_MIN\_WEIGHT algorithm, which favours the load balancing, is a perfect case for this test. The results we obtained with this load balancer are presented on Figure 4. On this figure, we plotted the whole execution time (including load balancing) according to the number of particles per cell. We can see that except for the small cases, we are always better than the other algorithm. On problems equal or larger than 2000 particles per cell, we reduce by 30% the execution time without load balancing (Baseline).

Now, if we compare the load balancing time of each strategy we can notice that TMLB\_MIN\_WEIGHT take on average 233 ms when RefineLB take 1 ms. As for GreedyLB, the load balancing is calculated in 14.5 ms. However, even if TMLB\_MIN\_WEIGHT is much more slower than the two other load balancers it is counterbalanced by the benefits obtained on the total execution time of the application.

In Fig. 5 we present the number of chares that migrate from one core to a new one for the same execution than the one depicted in Fig 4. We see that GreedyLB does not take into account this goal as almost all the chares migrate. RefineLB is mainly an incremental strategy that balances the load by

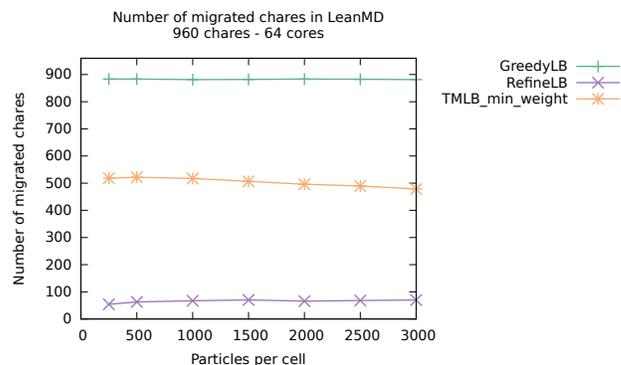


Fig. 5. Average number of migrated chares (among a total of 960 chares) for each load balancer and for each set of runs of LeanMD.

moving as few chares as possible, therefore, the number of migration is very small. The TMLB\_MIN\_WEIGHT strategy finds a good compromise between migration cost and other factors impacting the execution time (e.g. load, communication, topology). Without migration minimization the number of migrations is much higher (around 680 migrations) as the execution time is (approximately 5% increase), therefore this feature is necessary to achieve good performance.

### B. kNeighbor

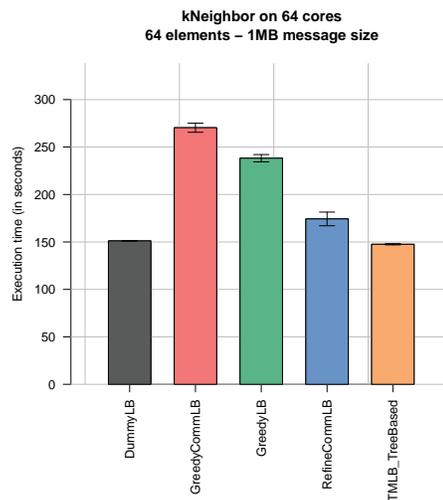


Fig. 6. Execution time (including load-balancing) of the KNeighbor application on 64 cores for different load balancing strategies with 64 chares and 1Mb messages.

kNeighbor is a application designed to simulate intensive communication between a fixed number of chares (7 by default). Our results are presented in Figure 6, 7 and 8.

We carried out these experiments with respectively 64, 128 and 256 elements (chares). We can see that for all these experiments, we are faster than all the other solutions. When there are only a few elements, no load balancer yields good performance when compared to the native charm++ load balancers. When we reach 256 elements, the native load balancers can achieve interesting improvements, especially

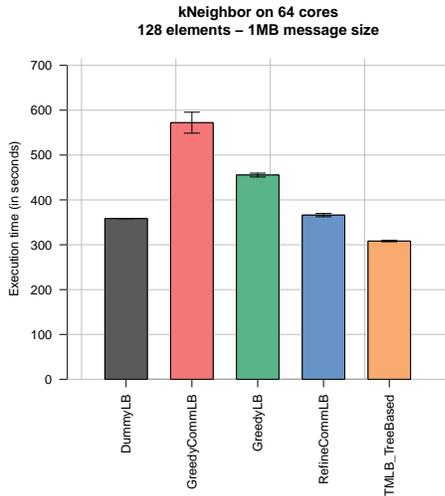


Fig. 7. Execution time (including load-balancing) of the KNeighbor application on 64 cores for different load balancing strategies with 128 chares and 1Mb messages.

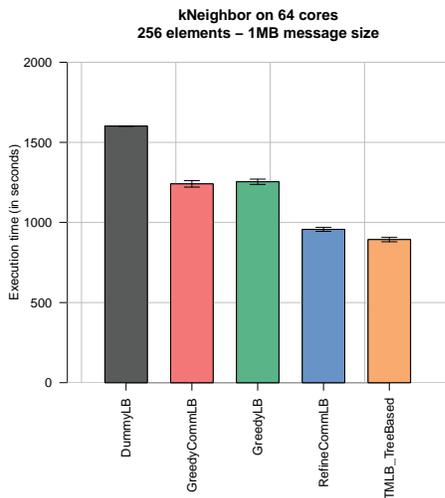


Fig. 8. Execution time (including load-balancing) of the KNeighbor application on 64 cores for different load balancing strategies with 256 chares and 1Mb messages.

RefineCommLB. However, TMLB\_TREEBASED manages to outperform it, by roughly 10%. Moreover we see that the relative performance of TREEMATCH improves with the input size.

The Figure 9 represents the execution time of each load balancing strategy used for our kNeighbor experiments. The first thing we can notice is that every load balancer follow a linear trajectory while the number of chares is doubled at each step on the x-axis. TMLB\_TREEBASED is clearly slower than the other strategy but give us a good chare placement which improve the total execution time as shown in Figures 6, 7 and 8.

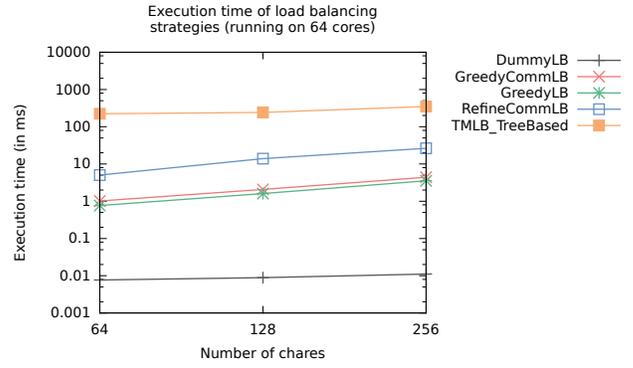


Fig. 9. Load balancing time of the different strategies vs. number of chares for the KNeighbor application.

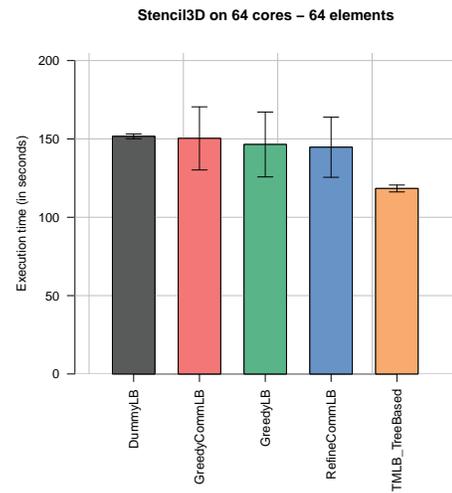


Fig. 10. Execution time (including load-balancing) of the Stencil3D application on 64 cores and 64 chares

### C. Stencil3D

Stencil3D is a 3 dimensionnal stencil with regular communication with some fixed neighbors. Because of this, it is not beneficial to apply a load balancing scheme every ten iterations. The best results we achieved, for each load balancer, was when we balanced the load *only once*, after ten iterations. The experiments presented in Figure 10 follows this principle. Like kNeighbor, Stencil3D is a communication-bound application. That is why we applied TMLB\_TREEBASED. We notice two important results. First, we obtain a gain of roughly 18% compared to the other strategies. Second, our algorithm offers a better execution time stability as shown by the error bars representing the standard deviation.

The load balancing time is very short for greedy strategies in Stencil3d experiments. Except for RefineCommLB which takes approximately 7.5 ms, the others greedy load balancers take less than 1 ms to determine the new chares assignment. Conversely, TMLB\_TREEBASED take on average 214.8 ms. As for the kNeighbor case, this load balancing time has to be compared to the total execution time of the application. The time needed by our strategy to find a good chare placement is

completely absorbed by the gain in execution time.

## VII. CONCLUSION

Efficiently executing high-performance applications on parallel computers is a hard task. One efficient solution consists in structuring the application and exposing its parallelism as much as possible in order to express all its parallelism. However, fine-grain parallelism raises the question of an efficient load-balancing.

In the literature, there exists many load balancing strategies. However, architectural advances have led to highly hierarchical computing platforms and therefore it is necessary to propose new solutions and strategies taking into account the load, the communication, the topology or the migration cost.

In this paper, we have studied two new load-balancing strategies and we have implemented them in the Charm++ computing environment. Both strategies address the issue of topology-aware load-balancing but one is targeted towards compute-bound applications while the other targets communication-bound applications. These solutions are based on the TREEMATCH library that is designed for mapping computation to tree-structured topologies and which have the advantage of using only qualitative information.

We have tested them on a distributed memory platform and compared them against standard Charm++ load balancing strategies. We have chosen real applications (LeanMD, Stencil3D and Kneighbor). Our results show that the proposed strategies lead to better execution times even if computing the load-balancing is higher when using TREEMATCH.

Future works are directed towards extending the scalability of the strategies by improving their parallelism and the gathering of the information required by them. For instance, we want to improve the adaptation of TMLB\_TREEBASED concerning the choice of the hierarchy level where the algorithm is distributed in order to improve its scalability.

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