

# Architecture based on dynamic graphs for the dynamic reconfiguration of farms of computers

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**Abstract**—In the last years, the computers have increased their capacity of calculus and networks, for the interconnection of these machines. The networks have been improved until obtaining the actual high rates of data transferring. The programs that nowadays try to take advantage of these new technologies cannot be written using the traditional techniques of programming, since most of the algorithms were designed for being executed in an only processor, in a nonconcurrent form instead of being executed concurrently in a set of processors working and communicating through a network. This paper aims to present the ongoing development of a new system for the reconfiguration of grouping of computers, taking into account these new technologies.

**Keywords**—Dynamic network topology, resource and task allocation, parallel computing, heterogeneous computing, dynamic reconfiguration

## I. INTRODUCTION AND MOTIVATION

THE use of clustering computing to solve computational problems has been the focus of high-performance computing community for more than two decades. The advances made in microprocessors and computer networks have caused the appearance of clusters or networks of workstations (NOWs) to be an alternative to the more and more expensive supercomputers. However, the demand of computing power continues growing as long as most of the available machines are underused. Due to this continuous growth of the capabilities of networks, there are posed multiple optimization problems associated with algorithms for the design of networks and topologies. For general optimization of hosts in farms of computers, a methodology of dynamic resources allocation is needed [1]–[3]. Nowadays, this is one of the main reasons of the existence of a special interest in searching new algorithms, which will enable the replacement of the traditional methods. The efficiency and possibility of scaling in parallel to the architectures of processors make the use of the traditional methods inapplicable in many cases [4].

The main problem designing a parallel or distributed algorithm resides in the communication and synchronization of processes for its concurrent execution in different processors. This is a very hard non-deterministic optimization problem that not allways have the best solution. In many cases, only an approximation can be calculated.

From the point of view of the heterogeneity of processors, a good parallel application for Heterogeneous Network of Computers (HNoC) must distribute computations unevenly,

taking into account, at least, the speed of the processors, the heterogeneous in terms of the network topology and the resources needed by each processor. The efficiency of the parallel application also depends on the accuracy of estimation of the speed of the processors of the HNoCs, which is difficult because the processors may have different speeds for different applications due to the differences in the set of instructions, the number of instruction execution units, the number of registers, the structure of memory hierarchy and so on [5].

From the point of view of the communications, one of the main problems of the implementation of networks of communication is the one of designing a network topology that could verify certain characteristics of trustworthiness, assuming this as a measurement, that evaluates the probability of success in the communication between pairs of processors. This is a non-trivial factor in the quality of services offered to all the computers. The evaluation of the exact parameters that determine the trustworthiness of a communication network is also a NP-hard problem [6], [7]. For this reason, an optimization of the topology of the net is needed. It must be assured that the temporary delay due to the communication and synchronization of the processes, is minor to the delay of processing the data by each processors. Also it is important to consider that when the problem is too much divided, the spent time to transmit data between computers and to synchronize them, exceeds the time of computation of that CPU.

The common communication network is usually heterogeneous. The speed and bandwidth of the network, between different pairs of processors, may differ significantly. This makes the problem of optimal distribution of computations and communications across the HNoC much more difficult than across a dedicated cluster of workstations interconnected with a homogeneous high-performance network. Other issue is that the common communication network can use multiple network protocols for communication between different pairs of processors. A good parallel application should be able to use multiple network protocols between different pairs of processors [8].

Our work focuses on the allocation of resources and tasks, and on the configuration of the topology of the network, by transferring the workload onto other computers of the farm, to find a dynamic matching between the tasks and the global resources of the NOWs that optimizes the application completion time. This will be done assuming a non-static and decentralized approach.

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## II. DEFINITIONS AND BACKGROUND

The NOWs can be seen as a weighted directed graph with costs either in the vertices (resources costs) and in the edges (communications between pair of nodes costs). The vertices of the graph represent the nodes of the NOWs and the edges, the physical communication between pair of nodes of the farm. Discretely, one node is an instance of one processor, that is, every processor is one node. When applying the concept of the graph to a distributed and heterogeneous environment (HNoC), the costs associated with these weights depend on various system characteristics, such as the processing speed of and the communication latency between network nodes. Each node of the NOW or of the HNoC can act as master or slave process: masters are entrusted to send the tasks to be done by the slaves nodes and to manage the synchronism between the processes. Slaves play the role of executing the tasks sent by the master process. In our case of study, all nodes are equally master or slaves.

In order to build a computing environment for farms of computers, it is also necessary to have an algorithm that requires the ability to predict the performance and the resource consumption of different cluster configurations. This algorithm is called the Resource Management System (RMS). The problem is that it is difficult to predict the computing time by a node after it receives some arbitrary load. Also, this will be even more difficult if we consider the variation in the topology of communication of the farm. The basic tasks of the RMS is to accept requests for resources by applications and allocate them from the pool of resources. This is a slightly approximation of a computer middleware. As all nodes are equally master or slaves, we need one special node, the supermaster, in where the RMS plays its role.

The RMS uses a predictive estimation based on a mathematical function (heuristic function  $\Upsilon$ ), in order to map tasks of the parallel application to the pool of resources. This heuristic function will be the one needed to define the graph partition and assigning the workload to each node. These techniques for predicting the performance of the dynamic system are nowadays based on queueing techniques and/or on historical techniques [9]. Making a comparison between layered queues and the historical model it is well known that the layered queue requires more CPU time to make the mean response time prediction whereas the historical predictions model are almost instantaneous. However queueing techniques are easier to implement with a minimum level of performance than the historical model. This is because designing a historical model involves specifying and validating how predictions will be made whereas the queueing model can be solved automatically [10]. Both techniques can be combined to take advantages of them.

The layered queueing performance model defines an application's queueing network. The solution strategy, in this case, involves dividing the problem into tasks depending on the resources, and corresponding to the tiers of servers in the system model generating an initial topology solution and then iterating with the historical method, solving and redimensioning the queues in each step of the algorithm until

the solution converge to an optimal distribution of resources, tasks and communications delays.

For the queue model it is necessary to define a queue structure for each node of the HNoC which will be shared by all the incoming requests (fig. 1). The nodes can be both clients (request information) and servers (process the information). The queue can be managed by a FCFS (First-Come, First-Served), LCFS (Last-Come, First-Served) or SIRO (Service In Random Order) policy

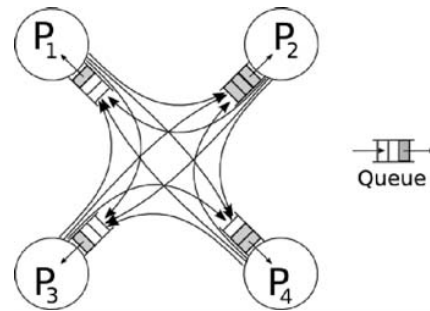


Fig. 1. Example of a HNoC with 4 nodes. Each server has its own queue for receiving the incoming requests from the rests of nodes of the farm.

The different queue models are defined by 6 factors, in shorthand notation, called Kendall's Notation, as  $A/B/C/X/Y/Z$  where [11]:

- A: the arrival process distribution. Distribution of probability assumed between arrivals.
- B: the service time distribution. Distribution of probability that gives the distribution of time of the service of a customer.
- C: the number of servers.
- X: maximum number of customers allowed in the system including those being in service. When this number is at the maximum value, arrivals are turned away.
- Y: the population size.
- Z: the discipline of the queue. Priority order of jobs in the queue.

Thus, solving the problem of the optimization of the global resources of the HNoC can be approached by solving the problem of finding the minimum path of the associated graph [12] taking into account the communication delays and the execution time per task of each processor.

## III. MATHEMATICAL MODEL

The HNoC system can be modelled as a weighted directed graph  $G_s$ , denoted by  $G_s(P, L, \tau, \delta)$  referred as the *SystemGraph*.  $P$  denotes a finite set of processors that represents the nodes or vertices of the graph  $G_s$ ;  $L$  is a finite set of links that represents the communication links between pair of processors: the edges of the graph  $G_s$ ; Each vertex  $p_i \in P$  is characterized by a set of system parameters (memory, frequency, operating system...), based on its available resources of the HNoC. Due to this, each processor suffers a processing weight  $\tau(p_i)$  that denotes the processing cost per unit of computation. Each link between two processors  $p_i$  and

$p_j$ , denoted by  $l_{i,j} \in L$ , has a link weight  $\delta_{i,j}$  that means the communication latency between those two nodes per transfer unit. If two nodes  $(p_i, p_j) \in P$  are not connected to each other then  $l_{i,j} = \infty$ . We assume that all nodes of the graph are connected to at least one node of the HNoC (connected graph) but we not enforce constraints on the network topology as this is not completely defined and can vary between two steps of the simulation of the problem that is being executed in the HNoC. It is necessary to define a neighbourhood function which will return the set of nodes that are linked with any node of the HNoC,

$$\forall p_i \in P : \text{neig}(p_i) = \{p_k\} \mid l_{i,k} \neq \infty$$

So, we must define another function  $\text{path}(p_i, p_j)$ , defined as

$$\forall p_i, p_j \in P : \text{path}(p_i, p_j) = \{p_k\}^*$$

where  $p_k^*$  is a sorted set of nodes where each node either  $p_k \in \text{neig}(p_i)$  or  $p_k \in \text{neig}(p_j)$  or  $p_k^n \in \text{neig}(p_k^{n-1})$ . It is necessary to define a latencies matrix  $C_L$  equal to the network latencies between any two processors,  $\forall p_i, \forall p_j \in P, C_{L,i,j} = \text{lat}(p_i, p_j)$ , which will depend also on the physical and data link network layer. For two adjacent nodes  $p_i, p_j, \in P, C_{L,i,j} = \text{lat}(p_i, p_j) = \delta_{i,j}$  but if  $p_i$  and  $p_j \in P$  are not adjacent in the HNoC, the latency will be defined as the sum of the links weights on the sortest path between them,

$$C_{L,i,j} = \text{lat}(p_i, p_j) = \sum (\delta_{p_k} \mid p_k \in \min(\text{path}(p_i, p_j)))$$

(fig. 2). The matrix  $C_L$  could be symmetric or not, since all communications could be different also in a duplex communication, because of the directed property of the graph.

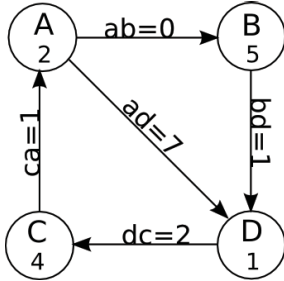


Fig. 2. Example of a System Graph  $G_S$ . The characteristics of the graph are: nodes  $P = \{A, B, C, D\}$ , links  $L = \{ca, ab, ad, bd, dc\}$ , processing weights  $\tau = \{2, 5, 4, 1\}$  communication latencies  $\delta = \{1, 0, 7, 1, 2\}$  and  $\text{neig}(A) = \{B, D\}$ ,  $\text{path}(C, D) = \{C, A, B, D\} \cup \{C, A, D\}$ , but  $\text{path}_{\min}(C, D) = \{C, A, B, D\}$

$$C_L = \begin{matrix} & \begin{matrix} A & B & C & D \end{matrix} \\ \begin{matrix} A \\ B \\ C \\ D \end{matrix} & \begin{pmatrix} 0 & 0 & 3 & 7 \\ 4 & 0 & 3 & 1 \\ 1 & 3 & 0 & 2 \\ 3 & 3 & 2 & 0 \end{pmatrix} \end{matrix}$$

The graph of minimum paths for a specific node of the graph  $G_s$ , denoted by  $G_m^a(P, L, \tau, \delta)$  will be defined as the graph that contain the minima paths from the node  $a \in P$  to any node of the graph (fig. 3).

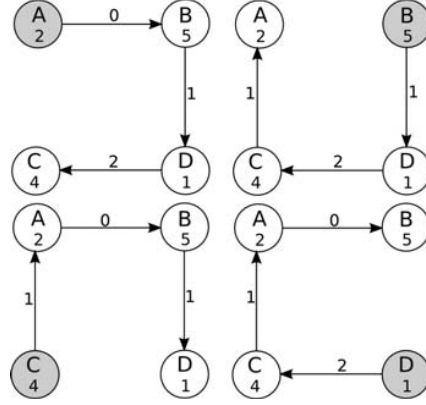


Fig. 3. Obtained graphs  $G_s$  for each node of the graph of the figure 2.

The application can also be modelled as a weighted directed graph  $G_a$ , denoted by  $G_a(T, D, \omega, \lambda)$  referred as the *ApplicationGraph*.  $T$  denotes a set of vertices of the graph that represents the tasks to be done.  $D$  represents a finite set of edges of the graph where  $\{(t_i, t_j) \mid t_i, t_j \in T\}$ .  $E_{i,j}$  represents the data dependency between two vertices  $t_i, t_j$ . Each vertex has a computation weight  $\omega(t_i), \forall t_i \in T$  that represents the amount of computations required by the task  $t_i$  to accomplish one step of the algorithm. Each edge has a value  $\lambda_{i,j}$  that represent the amount of data to be sent from  $v_i$  to  $v_j$ .

Thus, the execution time  $\Gamma$  of a task  $t_i \in T$  on a processor  $p_j \in P$ , assuming the worst case in which there is no-overlapping between computation and communication, is defined as:

$$\Gamma(t_i, p_j) = \omega(t_i) \times \tau(p_j) + \sum_{t_l \in \text{neig}(p_k)} \sum_{\substack{p_k \in P \\ k \neq j}} \lambda(t_i, t_l) \times \delta(p_j, p_k)$$

where  $\omega(t_i) \times \tau(p_j)$  represents the amount of computation required by the task  $t_i$  per processing cost per unit of computation.

Given a system graph  $G_S(P, L, \tau, \delta)$  and an application graph  $G_a(T, D, \omega, \lambda)$ , the objective is to map characteristics  $\Gamma : (T, D) \mapsto (P, L)$  for minimizing the function  $\Gamma$  based on the application requirements and the system constraints such as the topology of the system graph.

From the point of view of the queue prediction technique, we can assume that the HNoC can be modelled by a  $M/G/1/\infty/\infty/SIRO$  model where the arrival process distribution is a Markovian process [13], the service time is a general distribution referring to a independent arrivals to the system and there is only one server for that queue [14]. We must allow to any server to pop an item from the queue in an arbitrary order, according to a certain priority value. This characteristic forces the *SIRO* parameter of the queue. We will maintain only a queue per each server, but, from the point of view of the whole system, the queues will be modelled as a  $M/G/c/\infty/\infty/SIRO$ , where  $c$  is the number of nodes of the HNoC. The length of the queue (maximum number of jobs in the queue),  $L$ , will depend on the arrival rate  $\lambda$ , and on the

service rate  $\mu$  and will be calculated by the expression:

$$L = \frac{\lambda^2 E[S^2]}{2(1 - \rho)} + \rho$$

where  $\rho = \frac{\lambda}{\mu}$  and  $E[S^2]$  is the second moment of the expected value of the service rate random distribution  $S$ .

The historical modelling technique involves sampling performance metrics (response times, resources availability, communication delays...) and will associate these measurements with variables representing the workload being processed and the machines architecture. The historical function, in most cases, cannot be solved mathematically and it is necessary to solve it, by using an optimization method as a simplex or *tableau* algorithm.

#### IV. PROPOSAL

Until this moment, we have considered only a static network topology, that depends on the domain decomposition, defined before the execution of the algorithm or application in the HNoC; in those problems in which is not trivial defining a domain decomposition (i.e. access to data in distributed databases) would be useful to have a dynamic topology of communications, which can vary around the distribution of the data and the different latencies of the network, depending on the different connections between the nodes.

The model proposed for the reconfiguration of nodes of a HNoC will be based on a sufficiently ample language of communications. Using this language any node will be able to know in real time, what information contains any other node of the system (data middleware), without having to communicate first with the master node of that system. This language also will allow the nodes to modify their roles of master/slave depending on what value or data structure is needed and on what node has asked for it (fig. 4).

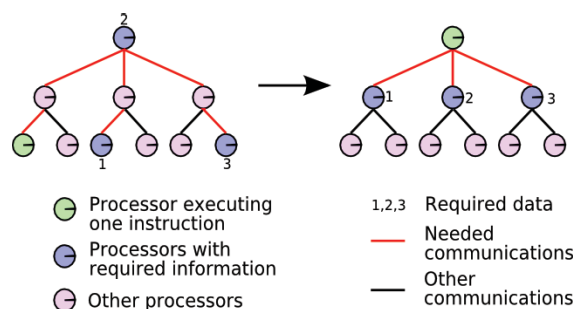


Fig. 4. Example of the reconfiguration of a HNoC applied to a distributed database. At least 3 nodes have changed its master/slave role, to adapt the HNoC network topology to the data distribution. This has been made in order to minimize the global delay for the execution of the query in the system.

The HNoC will be represented as a directed dynamic graph (as in figure 2) in which the different connections will have weights of edges (cost of moving directly from one vertex to another one) equals to the different delays from network and those due to the overload of the processors of the nodes. The vertex of the graph will represent each processors available at the HNoC. The information of each node of the graph

will contain the effective load of the processor, considering this as the availability to execute other processes. Also the node will contain as well, a statistic value proportional to the execution time of the processes in previous steps of the algorithm. Therefore, the edges of the graph will represent the connections between the available processors, according to a certain instant of the algorithm. These connections are statistically weighted according to the network delays, the time of transmission of the data through the net that depends as well on the network protocol, and the physical layer used for this communication. These two values will be important for the calculation of the optimized values of the historical function.

In addition to the nodes that are included in the HNoC, a super master node will exist. This node will be the one which will administer the minimum graphs that represents the path used by each node to communicate with the other ones (as in figure 3). The super master node will maintain the resulting graph of all the existing communications between any two nodes of the HNoC and also the execution times of each processor. With this information, and according to a statistical and heuristic function  $\Upsilon$ , this node will generate an optimal graph, probably different, for each node of the HNoC. These graphs will be calculated based on the communications that each node needs to make with any other one, its workbalance, the value  $\tau(p_i)$ , some historical values, ..., and they will be calculated according to some algorithm of minimum path for graphs (fig. 5). Knowing that all the weights of the vertices and of the edges of the graph are allways positive values, we could use algorithms based on Dijkstra [15] or Bellman-Ford [16].

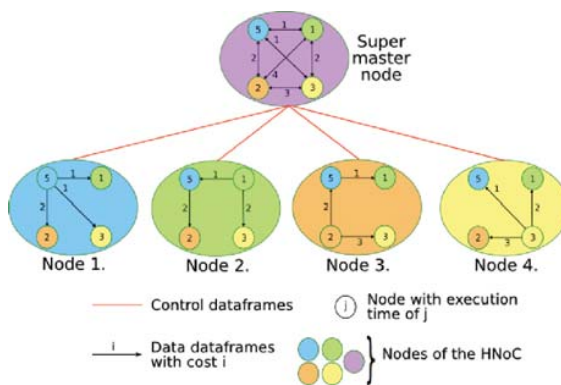


Fig. 5. HNoC formed by 5 processors, 4 nodes and 1 supermaster node. The supernode contains a complete-graph with all the possibles communication between each two nodes and the statistical value for the delays and effective load of each processor. The other nodes are dedicated to realize the calculus assigned by the supermaster node. Each of these nodes can play the roll of a master, a slave or even a mixed solution. In this example we have also to consider that all nodes contains the same information data. The supermaster node will calculate the minimum graphs for each processor and will communicate it to them. With these graphs, the other nodes know to which one must it send the information data. Each processor can resend the information to another node as a proxy.

In order to be able to reconfigure the HNoC the language of communications will include control dataframes and data dataframes. The data dataframes will contain the data needed for the execution of the algorithm in the HNoC, whereas the

control dataframes will be those with information about the execution times and commands, and will be sent for knowing what nodes have what information and what hierarchy exists between the different nodes of the HNoC. This will be possible by developing a monitoring layer that will advise the supermaster node on each event that occurs in any node of the HNoC.

The control dataframes will allow also, to any node, to join or exit the farm of computers dynamically, sending a specific command to the supermaster node, to be included on, or to be deleted from the grouping. When a computer join the group, the supermaster will calculate again the graph of minimum paths for each node of the farm, in order to put in context the new node with the rest of computers. This calculus will be done with the new parameters of the system. When a node leaves the grouping, it will advise the supermaster node and this unregistration of the node from the farm will cause again a reorganization of the nodes of the HNoC.

The main advantage of this system is to avoid that in the task of designing a HNoC, the administrator must be the one that design the architecture and topology of the HNoC in function of the accesses that are needed depending on the problem to study. Also to eliminate the necessity of distributing the resources among the different nodes in function of the available resources.

#### REFERENCES

- [1] R. Canal, J.M.I Parcerisa, and A. Gonzalez. Dynamic cluster assignment mechanisms. In *HPCA*, pages 133–, 2000.
- [2] R. Bhargava and L. John. Improving dynamic cluster assignment for clustered trace cache processors. Technical report, 2003.
- [3] K. Amiri, D. Petrou, G. Ganger, and G. Gibson. Dynamic function placement in active storage clusters. Technical report, 1999.
- [4] A. Lastovetsky. Scientific programming for heterogeneous systems - bridging the gap between algorithms and applications. In *PARELEC'06 IEEE Proceedings*, pages 3–8, 2006.
- [5] A. Lastovetsky and R Reddy. HeteroMPI: Towards a message-passing library for heterogeneous networks of computers. *Journal of Parallel and Distributed Computing*, 2005.
- [6] M.O. Ball. Computing network reliability. 1979.
- [7] J.S. Provan and M.O. Ball. The complexity of counting cuts and of computing the probability that a graph is connected. *SIAM Journal on Computing*, (12):777 – 788, 1983.
- [8] J.Dongarra and A. Lastovetsky. *An overview of heterogeneous high performance and grid computing*. American Scientific Publishers, 2006.
- [9] David A. Bacigalupo, Stephen A. Jarvis, Ligang He, Daniel P. Spooner, and Graham R. Nudd. Comparing layered queuing and historical performance models of a distributed enterprise application. In *IASTED International Conference on Parallel and Distributed Computing and Networks*, pages 608–613, 2005.
- [10] David A. Bacigalupo, Stephen A. Jarvis, Ligang He, D. Spooner, D. Pellych, and Graham R. Nudd. A comparative evaluation of two techniques for predicting the performance of dynamic enterprise systems. In *PARCO*, pages 163–170, 2005.
- [11] L. Kleinrock. *Queuing Systems: Theory*. Wiley, 1975.
- [12] Bassel R. Arafeh, Khaled Day, and Abderezak Touzene. A paradigm for allocating parallel application tasks to heterogeneous computing resources on the grid. In *PARCO*, pages 41–48, 2005.
- [13] B. Song, C. Ernemann, and R. Yahyapour. Parallel computer workload modeling with markov chains. In *Proceedings of the 10th Job Scheduling Strategies for Parallel Processing (JSSPP)*, volume 3277, pages 47–62. Lecture Notes in Computer Science, Springer-Verlag, 2004.
- [14] D. Gross and C.M. Harris. *Fundamentals on Queuing Theory*. Wiley, 1998.
- [15] Edsger. W. Dijkstra. A note on two problems in connexion with graphs. *Numerische Mathematik*, 1:269–271, 1959.
- [16] Richard Bellman. On a routing problem. *Quarterly of Applied Mathematics*, 16(1):87 – 90, 1958.