Network Topology Aware Scheduling of Collective Data Exchanges

Emin Gabrielyan, Roger D. Hersch
École Polytechnique Fédérale de Lausanne, Switzerland
{Emin.Gabrielyan,RD.Hersch}@epfl.ch

Abstract

We propose a method for the optimal scheduling of collective data exchanges relying on the knowledge of the underlying network topology. We introduce the concept of liquid schedules. Liquid schedules ensure the maximal utilization of a network's bottleneck links and offer an aggregate throughput as high as the flow capacity of a liquid in a network of pipes. The collective communication throughput offered by liquid schedules in highly loaded networks may be several times higher than the throughput of traditional topology-unaware scheduling techniques such as round-robin or random schedules. To create a liquid schedule we need to find the smallest partition of a set of transfers into subsets of mutually non-congesting transfers. For network topologies (switches, communication links) having equilibrated throughput capabilities, the number of combinations of non-overlapping subsets of mutually non-congesting transfers grows exponentially with the number of transfers. We propose several methods to reduce the search space without affecting the solution space. On a real 32 node computer cluster, the measured liquid throughputs scheduled according to our method are very close to the theoretical liquid throughputs.

Keywords: Optimal network utilization, collective data exchange, liquid schedules, network topology, topology-aware scheduling.

1. Introduction

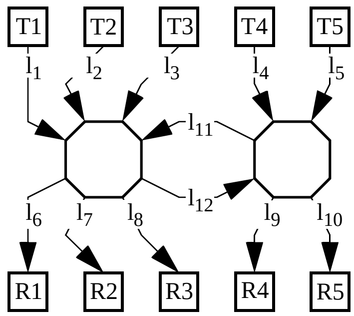
The interconnection topology is one of the key factors of a computing cluster. It determines the performance of the communications, which are often a limiting factor of parallel applications [1], [2], [3], [4]. Depending on the transfer block size, there are two opposite factors (among others) influencing the aggregate throughput. Due to communication protocol overhead, point to point throughput may decrease with the decrease of the packet size. However, smaller messages allow a more progressive utilization of network links. Intuitively, the data flow becomes liquid when the packet size tends to zero [5], [6]. In this paper we consider collective data exchanges between nodes where packet sizes are relatively large, i.e. the network latency is much smaller than the transfer time. The aggregate throughput of a collective data exchange depends on the underlying network topology and on the number of contributing processing nodes. The total amount of data together with the longest transfer time across the most loaded links (*bottlenecks*) gives an estimation of the aggregate throughput. We define this estimation as the *liquid* throughput of the network. It corresponds to the flow capacity of a non-compressible fluid in a network of pipes [6]. Due to transfers of data packets, congestions may occur and the aggregate throughput of a collective data exchange may be lower than the liquid throughput. The rate of congestions of a given data exchange may vary according to the chosen sequence of transfers.

The present contribution presents a scheduling technique for obtaining the liquid throughput. We limit ourselves to fixed packet sizes and neglect network latencies. Switches are assumed to be full cross-bar, also with negligible latencies.

Previous research efforts were focused on the optimization and scheduling of collective communications over wavelength division multiplexing optical networks [7] as well as of communications over satellite-switch time division multiplexing networks [8].

Unlike flow control based congestion avoidance mechanisms [9] [10], we establish schedules for the data transfers without trying to regulate the sending processors' data rate. We specifically address the problem of reaching the flow capacity of a fluid in a network by trying to optimally schedule the set of transfers of a collective data exchange.

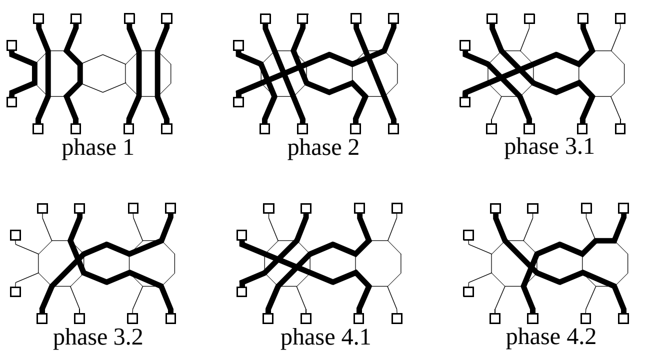
There are numerous applications requiring highly efficient network resources: parallel acquisition of multiple video streams each one forwarded to a set of target nodes [11], [12], voice-over-data traffic switching [13], [14] and high energy physics data acquisition and transmission from a large number of detectors to a cluster of processing nodes for filtering and event assembling [15], [16].



$$\left\{\begin{array}{c}\{l_1, l_6\}, \{l_1, l_7\}, \{l_1, l_8\}, \{l_1, \mathbf{l_{12}}, l_9\}, \{l_1, \mathbf{l_{12}}, l_{10}\}, \\ \{l_2, l_6\}, \{l_2, l_7\}, \{l_2, l_8\}, \{l_2, \mathbf{l_{12}}, l_9\}, \{l_2, \mathbf{l_{12}}, l_{10}\}, \\ \{l_3, l_6\}, \{l_3, l_7\}, \{l_3, l_8\}, \{l_3, \mathbf{l_{12}}, l_9\}, \{l_3, \mathbf{l_{12}}, l_{10}\}, \\ \{l_4, \mathbf{l_{11}}, l_6\}, \{l_4, \mathbf{l_{11}}, l_7\}, \{l_4, \mathbf{l_{11}}, l_8\}, \{l_4, l_9\}, \{l_4, l_{10}\}, \\ \{l_5, \mathbf{l_{11}}, l_6\}, \{l_5, \mathbf{l_{11}}, l_7\}, \{l_5, \mathbf{l_{11}}, l_8\}, \{l_5, l_9\}, \{l_5, l_{10}\}\end{array}\right\}$$

Fig. 1. Example of a data exchange composed of 25 transfers

For example, consider the all-to-all collective data exchange shown in Fig. 1. There are 5 transmitting processors (T1,... T5), each of them sending a packet to each of the receiving processors (R1... R5). The network consists of 12 links. Links l_{11} and l_{12} are the most loaded links, since each of them will be used by 6 transfers. The most loaded links are the bottlenecks of the collective data exchange. They have the longest active time. In the best case, the duration of a collective data exchange is as long as the active time of the bottleneck links.



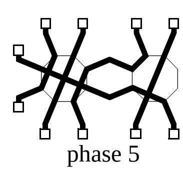


Fig. 2. Round-robin schedule of transfers (7 steps).

A *round-robin* schedule is carried out in 5 phases: *(1)* {T1→R1, T2→R2 ... T5→R5}, *(2)* {T1→R2, T2→R3 ... T5→R1}, etc. The round-robin schedule's throughput is however lower than the liquid throughput, since bottleneck links l_{11} and l_{12} are idle in phase 1 (Fig. 2). Phases 3 and 4 are carried out in two steps, since they contain congesting transfers.

Fig. 3 shows that a schedule achieving the liquid throughput for the considered collective data exchange exists.

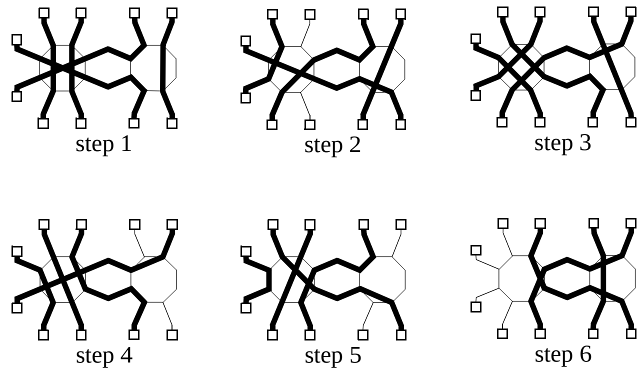


Fig. 3. An optimal schedule (6 steps).

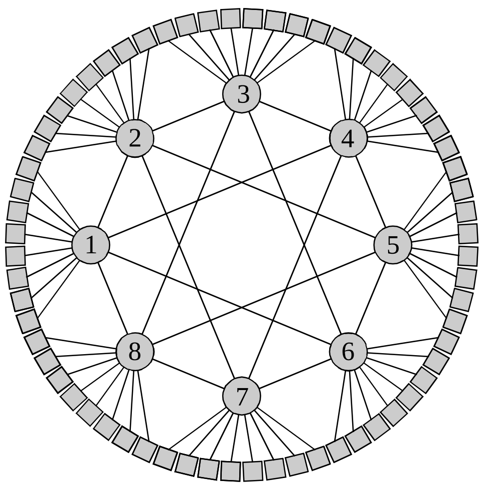
Section 2 shows how to describe the liquid throughput as a function of the number of contributing processing nodes and their underlying network topologies. The construction of liquid schedules is presented in section 3. In section 4, we present measurements for the considered sub-topologies and in section 5 we draw the conclusions.

2. Throughput as a function of sub-topology

Let us introduce a few test topologies for which liquid schedules will be computed.

In order to plot the throughput of collective data exchanges as a function of the network topology, we specify along an independent axis the number of contributing processing nodes as well as significant variations of their underlying network topologies. For the sake of simplicity, each node incorporates a transmitting and a receiving processor. The applications perform all-to-all data exchanges over the allocated nodes (each transmitting processor sends one packet to each receiving processor).

Let us create variations of processing node allocations on the Swiss-T1 cluster (called henceforth T1, see Fig. 4). The network of the T1 forms a K-ring [17] and has a static routing scheme. The throughputs of all links are identical, equal to 86*MB/s*. The cluster consists of 64 processors paired into 32 nodes [18].



Routing Table

	1	2	3	4	5	6	7	8
1	×	✓	**2**	✓	**4**	✓	**8**	✓
2	✓	×	✓	**7**	✓	**3**	✓	**5**
3	**2**	✓	×	✓	**4**	✓	**8**	✓
4	✓	**7**	✓	×	✓	**7**	✓	**3**
5	**4**	✓	**4**	✓	×	✓	**6**	✓
6	✓	**3**	✓	**7**	✓	×	✓	**1**
7	**8**	✓	**8**	✓	**6**	✓	×	✓
8	✓	**5**	✓	**3**	✓	**1**	✓	×

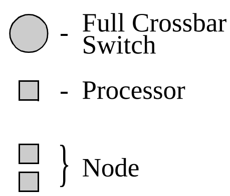


Fig. 4. Architecture of the T1 cluster computer.

Since there may be between 0 and 4 allocated nodes in front of each of 8 switches, we have $5^8 = 390625$ possible processing node allocations. With the given network topology and routing tables, we can compute for each combination of node allocation the liquid throughput of the all-to-all traffic.

Because of various symmetries within the network, many of these node allocations yield an identical liquid throughput. We enumerated 363 different node allocations corresponding each one to a different underlying network sub-topology. Each of these sub-topologies is characterized by its liquid throughput and the number of allocated nodes (see Fig. 5). Depending on the sub-topology, the liquid throughput for a given number of nodes may considerably vary.

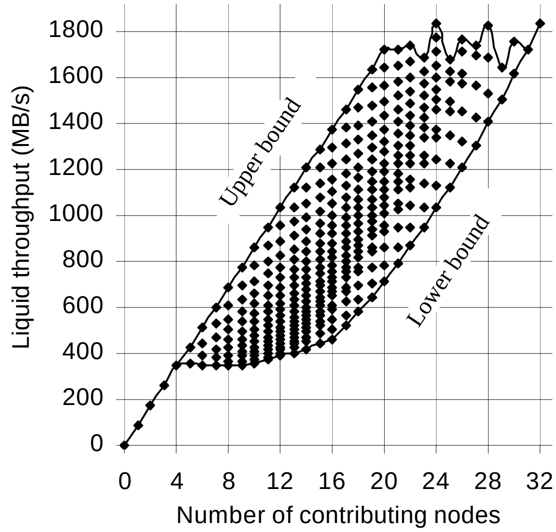


Fig 5. Liquid throughput in function of the number of nodes with variations according to sub-topologies.

These 363 topologies are placed on one axis, sorted first by the number of nodes and then according to their liquid throughput. Fig. 6 shows the predicted liquid throughput values together with the measured throughput of a round-robin schedule.

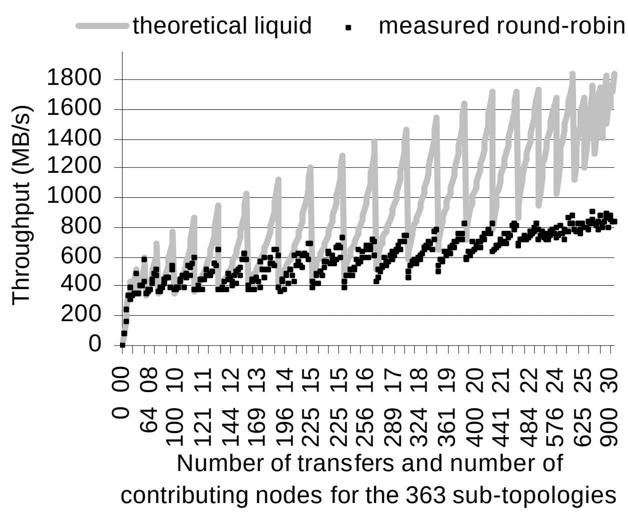


Fig. 6. Theoretical liquid throughput and measured round-robin schedule throughput for 363 network sub-topologies.

For many sub-topologies, the theoretical liquid throughput is twice as large as the round-robin throughput.

3. Liquid schedules

This section presents a method for building liquid schedules on any topology. As in many computer cluster networks, we assume a static routing scheme. The presented method is valid for any combination of transmitting and receiving processors performing any type of collective exchange (not limited to all-to-all exchanges). We neglect network latencies and assume a constant packet size for all data exchanges. A sending processor may transfer a packet to a given receiving processor not more than once.

Let us introduce a formal model of a collective data exchange.

DEFINITIONS. A *transfer* is a set of links (i.e. the links forming the path from a sending processor to a receiving processor). A *traffic* is a set of transfers (i.e. the transfers forming the collective exchange, see Fig. 1). A link l is *utilized* by a transfer x if $l \in x$. A link l is utilized by a traffic X if l is utilized by a transfer of X. Two transfers of a traffic X congest if they use a common link. A sub-traffic of X (a subset of X) is *simultaneous* if it forms a collection of non-congesting transfers.

A simultaneous subset of a traffic is processed in the time frame of a single transfer. The *load* of a link l in the traffic X is the number of transfers in X using l. The maximally loaded links are called *bottlenecks*. The *duration* $\Lambda(X)$ of a traffic X is the load of its bottlenecks. The size of the traffic $\#(X)$ is the number of its transfers. The *liquid throughput* of a traffic X is the ratio $\#(X) / \Lambda(X)$ multiplied by the single link throughput.

For example, the traffic X shown in Fig. 1 has a number of transfers $\#(X) = 25$ and the duration of the traffic is $\Lambda(X) = 6$. Therefore the aggregate liquid throughput is the ratio $25/6$ of a single link throughput, i.e. $(25/6) \times 100 MB/s = 416.67 MB/s$, assuming a single link throughput of 100*MB/s*.

3.1. Partitioning

A *partition* of X is a disjoint collection of non-empty subsets of X whose union is X [19]. A *schedule* α of a traffic X is a collection of simultaneous sub-traffics of X partitioning the traffic X. A *step* of a schedule α is an element of the schedule α. The *length* $\#(\alpha)$ of a schedule gives the number of steps in α. A schedule of a traffic is *optimal* if the traffic does not have any shorter schedule. If the length of a schedule is equal to the duration of the traffic, then the schedule is *liquid*. A liquid schedule is optimal, but the inverse is not always true, meaning that a traffic may not have a liquid schedule. Fig. 7 shows a liquid schedule for the collective traffic shown in Fig 1.

The duration of a traffic X is the load of its bottlenecks. If a schedule is liquid, then each of its steps must use all bottlenecks. Inversely, if all steps of a schedule use all bottlenecks, the schedule is liquid.

$$
\left\{
\begin{array}{ccc}
\left\{\begin{array}{c} \{l_1, \mathbf{l_{12}}, l_9\}, \\ \{l_2, l_7\}, \\ \{l_3, l_8\}, \\ \{l_4, \mathbf{l_{11}}, l_6\}, \\ \{l_5, l_{10}\} \end{array}\right\}
&
\left\{\begin{array}{c} \{l_1, \mathbf{l_{12}}, l_{10}\}, \\ \{l_2, l_6\}, \\ \{l_4, \mathbf{l_{11}}, l_7\}, \\ \{l_5, l_9\} \end{array}\right\}
&
\left\{\begin{array}{c} \{l_1, \mathbf{l_8}\}, \\ \{l_2, \mathbf{l_{12}}, l_9\}, \\ \{\mathbf{l_3}, l_6\}, \\ \{l_4, l_{10}\}, \\ \{l_5, \mathbf{l_{11}}, l_7\} \end{array}\right\}
\\
\text{step 1} & \text{step 2} & \text{step 3}
\\
\left\{\begin{array}{c} \{l_1, l_7\}, \\ \{l_2, \mathbf{l_8}\}, \\ \{\mathbf{l_3}, \mathbf{l_{12}}, l_9\}, \\ \{l_5, \mathbf{l_{11}}, l_6\} \end{array}\right\}
&
\left\{\begin{array}{c} \{l_1, l_6\}, \\ \{l_2, \mathbf{l_{12}}, \mathbf{l_{10}}\}, \\ \{\mathbf{l_3}, l_7\}, \\ \{\mathbf{l_4}, \mathbf{l_{11}}, \mathbf{l_8}\} \end{array}\right\}
&
\left\{\begin{array}{c} \{\mathbf{l_3}, \mathbf{l_{12}}, \mathbf{l_{10}}\}, \\ \{\mathbf{l_4}, \mathbf{l_9}\}, \\ \{\mathbf{l_5}, \mathbf{l_{11}}, \mathbf{l_8}\} \end{array}\right\}
\\
\text{step 4} & \text{step 5} & \text{step 6}
\end{array}
\right\}
$$

Fig. 7. A liquid schedule for the collective traffic shown in Fig. 1. Bold links in a step indicate bottlenecks in the reduced traffic, i.e. the original traffic minus the transfers of the preceding steps.

The necessary and sufficient condition for the liquidity of a schedule is that all bottlenecks be used by each step of the schedule. Since a simultaneous sub-traffic of X is defined as a *team* of X, if it uses all bottlenecks of X, an equivalent condition for the liquidity of a schedule α on X is that each step of α be a team of X.

Our strategy for finding a liquid schedule will therefore rely on searching for simultaneous sub-traffics using all bottlenecks, i.e. teams of a traffic. Hence, we need to partition a traffic by collections of teams (whenever possible).

Let us show that by removing an element (step) from a liquid schedule, we form a new liquid schedule on the remaining traffic. Note that the remaining traffic may have additional bottlenecks. For example, in Fig. 7, from step 3 on, links $\boldsymbol{l_3}$ and $\boldsymbol{l_8}$ appear as additional bottlenecks. Emerging additional bottlenecks allow us to reduce the search space when creating a liquid schedule.

THEOREM 1. Let α be a liquid schedule on *X* and *A* be a step of α. Then $\alpha - \{A\}$ is a liquid schedule on $X - A$.

PROOF. Clearly *A* is a team of *X*. Remove the team *A* from *X* so as to form a new traffic $X - A$. The duration of the new traffic $X - A$ is the load of the bottlenecks in $X - A$. Bottlenecks of $X - A$ include the bottlenecks of *X*. The load of a bottleneck of *X* is decreased by one in the new traffic $X - A$ and therefore the duration of $X - A$ is the duration of *X* decreased by one, i.e. $\Lambda(X - A) = \Lambda(X) - 1$. The schedule α without the element *A* is a schedule for $X - A$ with the previous length decreased by one. Therefore the new schedule $\alpha - \{A\}$ has as many steps as the duration of the new traffic $X - A$. Hence $\alpha - \{A\}$ is a liquid schedule on $X - A$.

In other words, if the traffic has a liquid schedule, then a schedule reduced by one team is a liquid schedule on the reduced traffic. The repeated application of Theorem 1 implies that any non-empty subset of a liquid schedule is a liquid schedule on the correspondingly reduced traffic.

3.2. Construction

THEOREM 2. If, by traversing each team *A* of a traffic *X* none of the sub-traffics $X - A$ has a liquid schedule, then the traffic *X* does not have a liquid schedule either.

PROOF. Let us suppose that *X* has a liquid schedule α. Then a step *A* of α shall be a team of *X*. Further, according to Theorem 1 the schedule $\alpha - \{A\}$ shall be a liquid schedule for $X - A$. Therefore for at least one team *A* of *X* the sub-traffic $X - A$ has a liquid schedule. This proves the theorem by contraposition.

Theorem 2 implies that if *X* has a liquid schedule at least one team *A* of *X* will be found, such that the sub-traffic $X - A$ has a liquid schedule β. Obviously $\beta \cup \{A\}$ will be a liquid schedule for *X*.

Let us give an overall view to the liquid schedule search algorithm. The algorithm recursively searches for a solution by traversing a tree in depth-wise order (Fig. 8). The root of the tree is the original traffic *X*. Associated to the traffic *X* is the collection of all possible steps of a liquid schedule $\{A_1, A_2, \ldots, A_n\}$. Successor nodes are formed by subtraffics $X - A_1$, $X - A_2, \ldots$ $X - A_n$. Each of these successor nodes has its own collection of all possible steps. As before, each member of this collection will produce successor nodes at the next level of the tree.

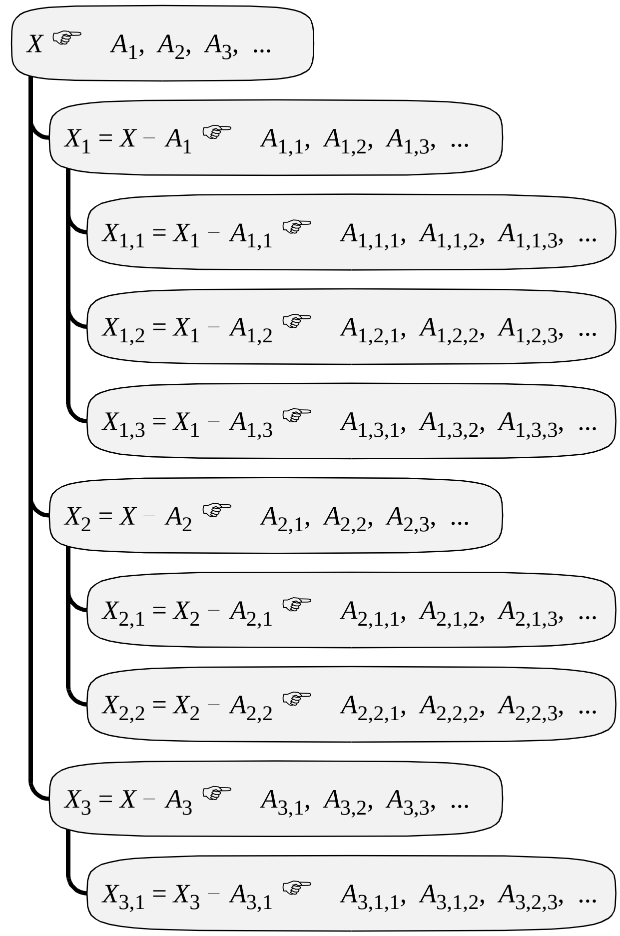


Fig. 8. Liquid schedule search tree. The symbol "☞" points to all possible steps for the current reduced traffic.

Let us discuss how to build the collection of all possible steps for the current node. For being liquid, it is sufficient that all the steps of a schedule be teams of the original traffic *X*. A possible step at each sub-traffic is any team of *X* formed by not yet carried out transfers, i.e. each team *A* of the original traffic *X* included in the current sub-traffic $X_{reduced}$, i.e. $\{A \in \Im(X) | A \subset X_{reduced}\}$, the operator $\Im$ associating with a traffic the set of all its teams.

We would like to reduce the search space. Instead of forming the set of possible steps by using teams of the original traffic $\{A \in \Im(X) | A \subset X_{reduced}\}$, we propose to form the set of all possible steps at the current node using all teams of the current sub-traffic, i.e. $\Im(X_{reduced})$. It can be shown that the number of teams of the current subtraffic

$\Im(X_{reduced})$ is smaller or equal to the number of teams of the original traffic whose transfers belong to the current subtraffic, i.e.

$\#(\Im(X_{reduced})) \leq \#(\{A \in \Im(X) | A \subset X_{reduced}\})$.

Therefore less possible teams need to be considered when building the schedule and the solution space is not affected, since theorem 2 is valid at any level of the search tree.

By traversing the tree in depth-wise order, we cover the full solution space. A solution is found when the current node (sub-traffic) forms a single team. The path from the root to that leaf node forms the set of teams yielding the liquid schedule. A node presents a dead end if it is not possible to create a team out of that sub-traffic. In that case we have to backtrack to evaluate other choices. Evaluation of all choices ultimately leads to a solution if it exists.

If a solution exists for *X*, then the algorithm will find it. If the algorithm does not find a solution for *X*, and since we explored the full solution space, we conclude that *X* does not have a liquid schedule.

Let us describe a further simple and efficient search space reducing technique.

DEFINITIONS. A simultaneous subset *A* of a traffic *X* is *full* with respect to *X* if each transfer of $X - A$ is in congestion with a transfer of *A*. A team of *X* is called *full* team if it is a full simultaneous subset of *X*.

Let us modify a liquid schedule so as to convert one of its teams into a full team. Let a traffic *X* have a liquid schedule α. Let *A* be a step of α. If *A* is not a full team of *X*, then, by moving the necessary transfers from other steps of α, we can convert step *A* to a full team. Evidently, the properties of liquidity (partitioning, simultaneousness and length) of α will not be affected. Therefore if *X* has a solution then it has also a solution when one of its steps is full, hence the choice of the teams in the construction may be narrowed from the set of all teams to the set of full teams only. Fig. 7 shows a liquid schedule constructed with full teams.

In order to be able to explore the full solution space for obtaining a liquid schedule, we need to successively build all full teams. We designed a procedure capable of generating (without repetitions) all full teams of an arbitrary traffic. It first builds *skeletons*, an intermediate collection of teams from a sub-traffic including only those transfers which comprise bottlenecks. Then it expands each skeleton by applying variations of all non-congesting transfers in order to build up all full teams.

As briefly described in the annex, the problem of creating a liquid schedule seems to be a more constrained problem than the general graph coloring problem.

4. Results

Let us compare the predicted theoretical values of the liquid throughputs with the measurements of the actual data exchanges carried out according to the liquid schedules we have found.

Fig. 9 shows the measured aggregate throughput of an all-to-all collective data exchange executed on a T1 computer cluster, optimized by applying our liquid schedule based traffic partitioning technique. Each black dot represents the median of 7 measurements. The horizontal axis represents the 363 sub-topologies as well as the number of contributing nodes. Processor to processor transfers have a

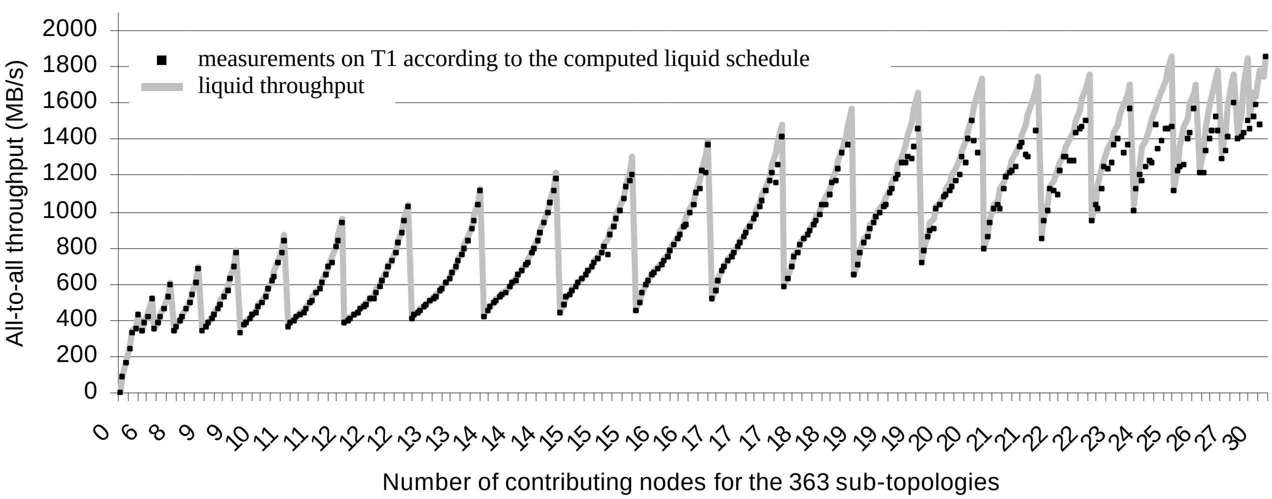


Fig. 9. Predicted liquid throughput and measured throughput according to the computed liquid schedule.

size of 5*MB*, transferred as a single message of 5*MB*. The measured all-to-all aggregate throughputs (black dots) are close to the theoretically computed liquid throughput (gray line). For many sub-topologies, the proposed scheduling technique allows to increase the aggregate throughput by a factor of two compared with a simple round-robin schedule (Fig. 6).

Thanks to the presented search space reduction algorithms, the computation time of a liquid schedule takes for more than 97% of the considered sub-topologies of the T1 cluster less than 1/10 of a second on a single Compaq 500MHz Alpha processor.

5. Conclusion

We propose a method for scheduling collective data exchanges in order to obtain an aggregate throughput equal to the network's liquid throughput. This is achieved by building at each step of the schedule mutually non-congesting sets of transfers using all bottleneck links. Exploration of the full solution space yields a liquid schedule if it exists. The proposed search space reduction techniques make the approach practical for networks having in the order of ten interconnected crossbar switches.

On the Swiss T1 cluster computer, the proposed scheduling technique allows for many sub-topologies to increase the collective data exchange throughput by a factor of two.

In the future, we intend to explore how to extend the presented scheduling technique in order to dynamically reschedule collective data exchanges when the set of planned exchanges evolves over time.

Annex

The search for a liquid schedule requires to partition the traffic into a set of non-overlapping mutually non-congesting transfers. The problem can also be formulated as a graph coloring problem [20], [21]. Vertices of the graph are formed by transfers. Edges between vertices represent congestions between transfers.

Fig. 10 shows the graph whose vertices are to be colored for the collective data exchange of Fig. 1. Vertex $x_{n,m}$ corresponds to a transfer from an emitting processor *n* to a receiving processor *m*. For example vertex $x_{4,1}$ represents

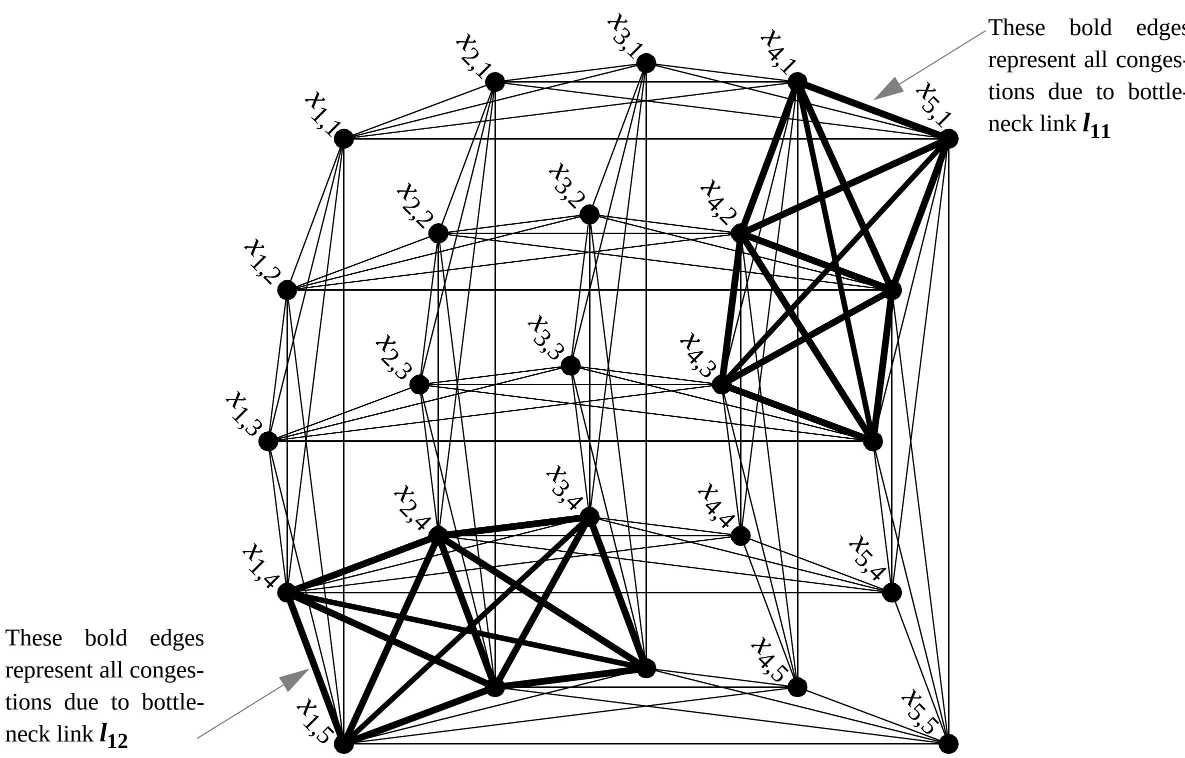


Fig. 10. Graph corresponding to the data exchange shown in Fig. 1. The 25 vertices of the graph represent the transfers. The edges represent congestion relations between transfers, i.e. each edge represents one or more communication links shared by two transfers.

the transfer T4→R1={l_4, $\mathbf{l_{11}}$, l_6}. The bold edges of the graph show congestions of transfers due to specific bottleneck links.

Whenever a liquid schedule exists, an optimal solution of the graph coloring problem is a liquid schedule. The chromatic number of the graph's optimal coloring is the length of the liquid schedule. Vertices having the same color represent a step of the liquid schedule.

The graph to be colored is characterised by the high density of its edges. We can label each edge of the graph by the link(s) causing the congestion. An all-to-all data exchange on the Swiss T1 cluster with 32 transmitting and 32 receiving processors forms a graph with $32 \times 32 = 1024$ vertices and 48704 edges. The approach we propose allows to compute in advance the chromatic number of the graph's optimal coloring (length of the liquid schedule). Furthermore, we further reduce the problem by first trying to "color" vertices having edges representing all bottleneck links (creation of teams). Then we work on the reduced graph, formed by the original graph minus the colored vertices (forming teams on sub-traffics). This suggests that our problem is a more constrained problem than the general graph coloring problem. It remains to be checked how our solution compares with solutions to variants of the graph coloring problem.

References

[1] H. Sayoud, K. Takahashi, B. Vaillant, "Designing communication network topologies using steady-state genetic algorithms", IEEE Communications Letters, Vol. 5, No. 3, March 2001, 113-115.

[2] Pangfeng Liu, Jan-Jan Wu, Yi-Fang Lin, Shih-Hsien Yeh, "A simple incremental network topology for wormhole switch-based networks", Proc. 15th International Parallel and Distributed Processing Symposium, 2001, 6-12.

[3] P.K.K. Loh, Wen Jing Hsu, Cai Wentong, N. Sriskanthan, "How network topology affects dynamic loading balancing", IEEE Parallel & Distributed Technology: Systems & Applications, Vol. 4, No. 3, 25-35.

[4] V. Puente, C. Izu, J. A. Gregorio, R. Beivide, J. M. Prellezo, F. Vallejo, "Improving parallel system performance by changing the arrangement of the network links", Proc. of the International Conference on Supercomputing, May 2000, 44-53.

[5] M. Naghshineh, R. Guerin, "Fixed versus variable packet sizes in fast packet-switched networks", Proc. Twelfth Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM '93., Networking: Foundation for the Future, IEEE Press, Vol. 1, 1993, 217-226.

[6] Benjamin Melamed, Khosrow Sohraby, Yorai Wardi, "Measurement-Based Hybrid Fluid-Flow Models for Fast Multi-Scale Simulation", DARPA/NMS BAA 00-18 AGREEMENT No. F30602-00-2-0556, *http://www.darpa.mil/ito/research/nms/meetings/nms2001apr/Rutgers-SD.pdf*

[7] J.-C. Bermond, L. Gargano, S. Perennes, A. A. Rescigno, and U. Vaccaro, "Efficient collective communication in optical networks", Proc. of ICALP'96. Lecture Notes in Computer Science, 574-585, 1996.

[8] R. Jain, G. Sasaki, "Scheduling packet transfers in a class of TDM hierarchical switching systems", IEEE International Conference on Communications ICC '91, Vol. 3, 1991, 1559-1563.

[9] Dah-Ming Chiu, Raj Jain, "Analysis of the increase and decrease algorithms for congestion avoidance in computer networks", Computer Networks and ISDN Systems, 1989, Vol. 17, 1-14.

[10] H. Ozbay, S. Kalyanaraman, A. Iftar, "On rate-based congestion control in high-speed networks: Design of an H-infinity based flow controller for single bottleneck", Proc. of the American Control Conference, June 1998, 2376-2380.

[11] S.-H.G. Chan, "Operation and cost optimization of a distributed server architecture for on-demand video services", IEEE Communications Letters, Vol. 5, No. 9, Sept. 2001, 384-386.

[12] Dinkar Sitaram, Asit Dan, *Multimedia Servers*, Morgan Kaufmann Publishers, San Francisco California, ISBN 1-55860-430-8, 2000, 69-73.

[13] H.323 Standards, *http://www.openh323.org/standards.html*

[14] D.A. Fritz, D.W. Moy, R.A. Nichols, "Modeling and simulation of Advanced EHF efficiency enhancements", Proc. of Military Communications Conference, IEEE MILCOM 1999, Vol. 1, 354-358.

[15] ATLAS Collaboration, CERN, Technical Progress Report, *http://press.web.cern.ch/Atlas/GROUPS/DAQTRIG/TPR/PDF_FILES/TPR.bk.pdf*

[16] Large Hadron Collider, Computer Grid project, CERN, 20.09.2001, *http://press.web.cern.ch/Press/Releases01/PR10.01EGoaheadGrid.html*

[17] P. Kuonen, "The K-Ring: a versatile model for the design of MIMD computer topology", Proc. of the High-Performance Computing Conference (HPC'99), San Diego, USA, April 1999, 381-385.

[18] Pierre Kuonen, Ralf Gruber, "Parallel computer architectures for commodity computing and the Swiss-T1 machine", EPFL Supercomputing Review, Nov 99, pp. 3-11, *http://sawww.epfl.ch/SIC/SA/publications/SCR99/scr11-page3.html*

[19] Paul R. Halmos, *Naive Set Theory*, Springer-Verlag New York Inc, ISBN 0-387-90092-6, 1974, 26-29.

[20] G. Campers and O. Henkes and J. P. Leclerq "Graph Coloring Heuristics: A Survey, Some New Propositions and Computational Experiences on Random and '{L}eighton's' Graphs" Proc. Operational Research, 917-932, 1988.

[21] A. Hertz and D. de Werra "Using Tabu Search Techniques for Graph Coloring" in Computing(39) 345-351, 1987.