The Analysis and Optimization of Collective Communications on a Beowulf Cluster

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20 December 2002

1 Talk Outline

1. talk outline
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3. the Beowulf cluster ‘Bunyip’
4. types of collective communications: all-gather, all-reduce and reduce-scatter
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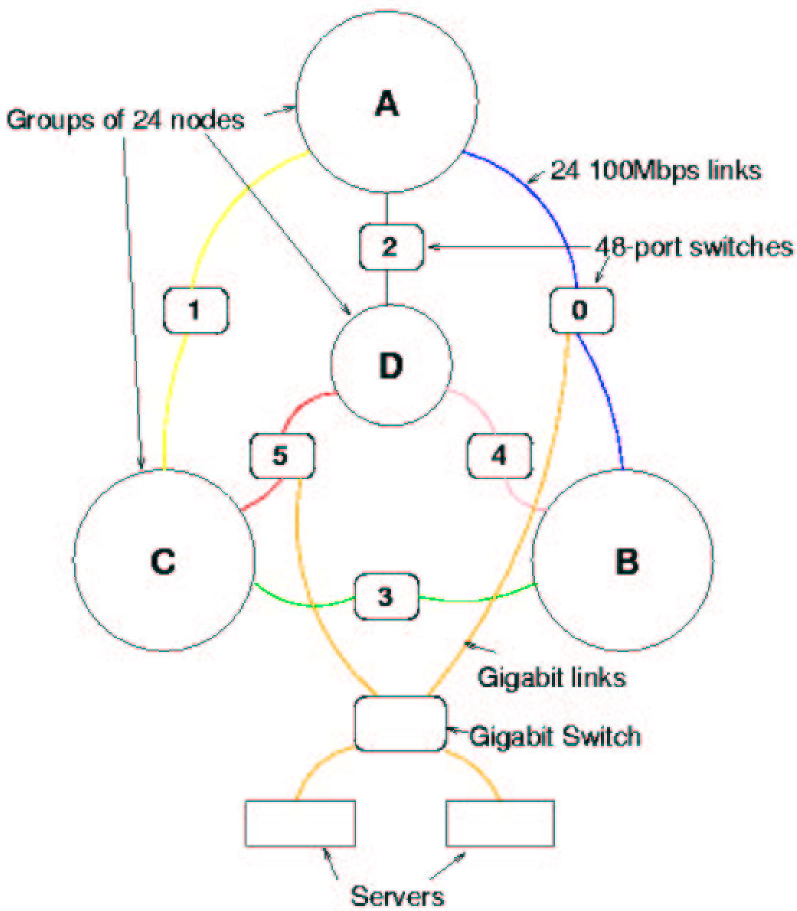
2 Motivations for Optimizing Collective Communications

- clusters made from commercial-off-the-shelf (COTS) networks are increasingly popular
  - eg. Beowulf clusters built from switch-based networks
- such networks typically slow; also may be different from vendor-designed networks (eg. contention-free)
  - optimization of collective communications is thus particularly important
  - may require different techniques to the 'traditional algorithms' built for networks on custom-made vendor-designed parallel computers
- our goal: to evaluate and understand collective communication performance for COTS network clusters

3 The Beowulf cluster 'Bunyip'



- 550 MHz dual Pentium III nodes, in 4 groups of 24
- each node has 3 100 Mb NICs
  - can communicate with 3 other nodes simultaneously
- contention-free switches
- 'Bunyip' is an monster in Australian mythology
- won Gordon-Bell Award for Price/Performance in 2000
- (MPI) communication startup cost is $\alpha = \alpha_s + \alpha_r = 24\mu s + 180\mu s$;

  bandwidth is 8 MB/s $(= 8/\beta)$,

  ie. communication cost per double is $\beta = \beta_s + \beta_r = 0.082\mu s + 1.063\mu s$

4 Types of Collective Communications

- All-Gather:

  start: node i, $1 \leq i \leq p$, has n words of data ($x^i_{1:n}$)

  end: all nodes have all of the pn data ($x^1_{1:n}, \ldots, x^p_{1:n}$)

- Reduce-Scatter:

  start: node k, $1 \leq k \leq p$, has np words of data ($y^k_{1:p,\ 1:n}$)

  end: node i has n words of summed data ($x^i_{1:n}$, $\quad x^i_j = \Sigma^p_{k=1} y^k_{i,j}$)

- All-Reduce

  start: node i, $1 \leq i \leq p$, has n words of data ($y^i_{1:n}$)

  end: all nodes have n words of summed data ($x_{1:n}$, $\quad x_j = \Sigma^p_{k=1} y^k_j$)

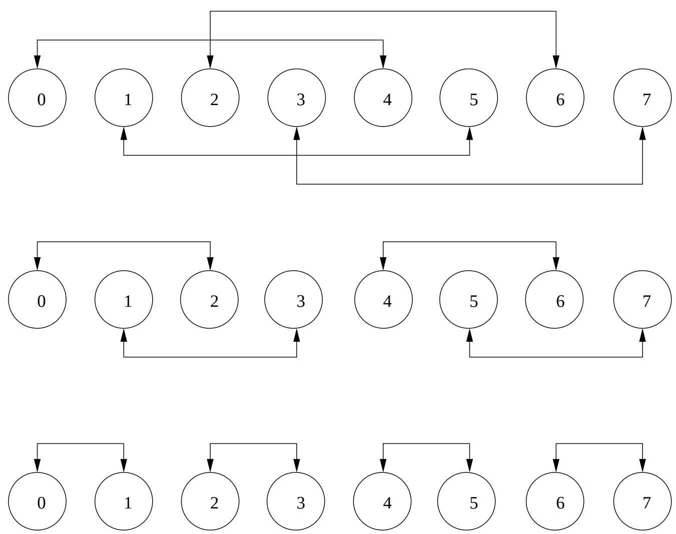
- these operations are widely-used (e.g. in dense linear algebra) and are in the MPI standard

- as we can model the time to send a message: $t = \alpha + \beta n = (\alpha_s + \alpha_r) + (\beta_s + \beta_r) n$,

  we similarly can have performance models for collective communications, e.g. $t^{ag} = f(n, p, \alpha_s, \alpha_r, \beta_r, \beta_s)$

5 Algorithms: traditional

- widely-used; good performance on traditional parallel computers
- bi-directional exchange:



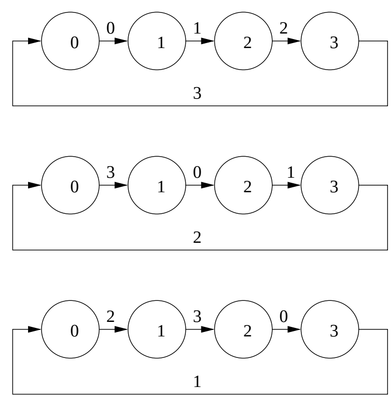
$$t^{ag} = \alpha \log_2 p + (p-1)(\beta n)$$
$$t^{ar} = \log_2 p(\alpha + \beta n)$$

- fan-in/fan-out: slowest, but often used

- recursive-halving/doubling: (v. complex for non-power-of-2 p!)

$$t^{ag} = t^{rs} + \log_2 p(\alpha + \beta \frac{n}{2})$$
$$t^{rs} = \alpha \log_2 p + (p-1)(\beta n)$$
$$t^{ar} = 2(\alpha \log_2 p + (p-1)(\beta \frac{n}{p}))$$

- ring (rotation) – no contention :



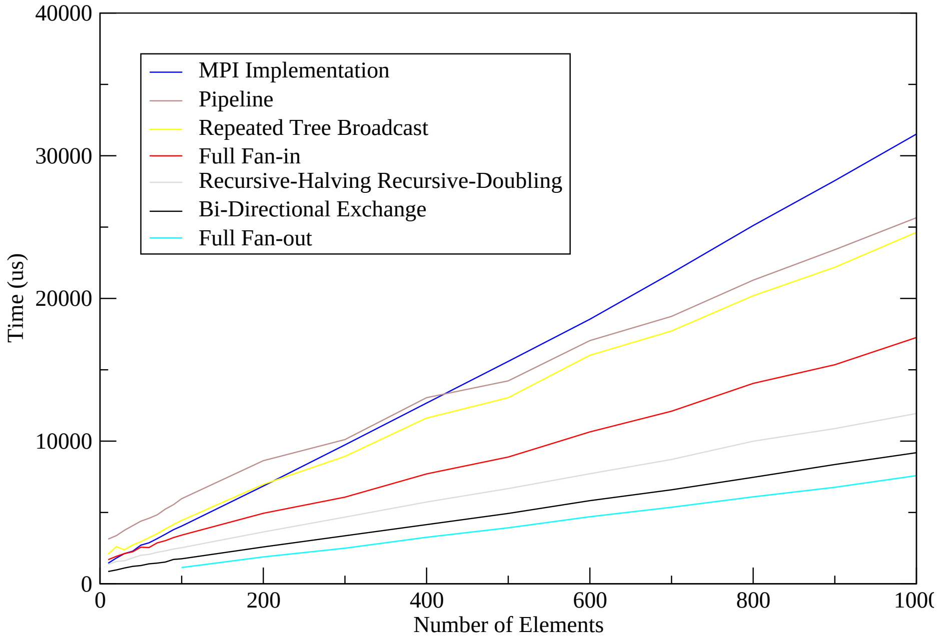
$$t^{ag} = t^{rs} = t^{ar} = (p-1)(\alpha + \beta n)$$

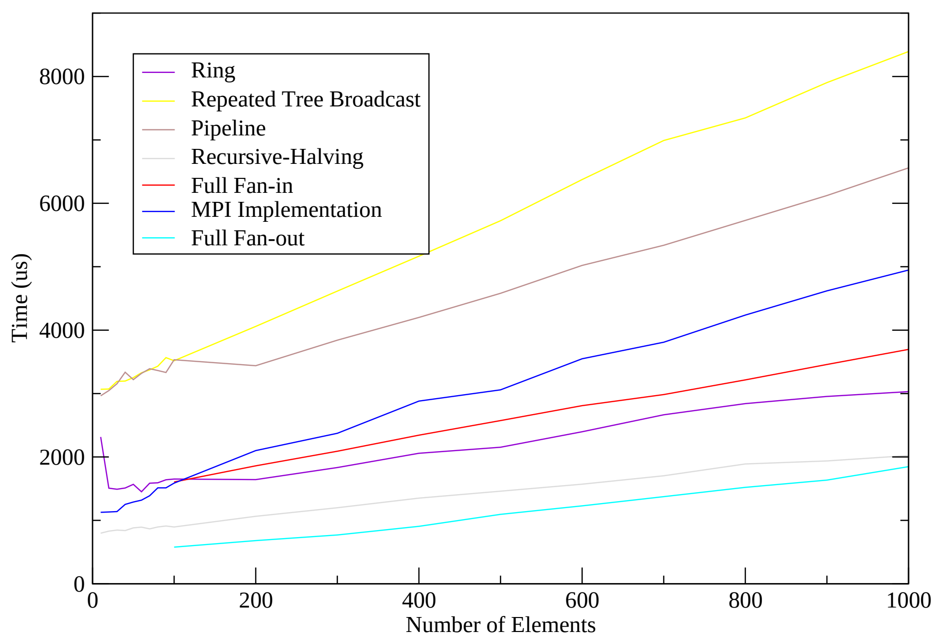
- above models assume an exchange is as fast as a single message

6 Algorithms: based on repeated sub-operations

- tree-like and ring-like patterns occur frequently in dense linear algebra
- in the case of All-Gather:
  - tree: binary-tree broadcast from each node i, $1 \leq i \leq p$
    $t^{rs} = p \log_2 p(\alpha + \beta n)$ (no overlap) $t^{ag} \approx \min[\log_2 p, 2] p(\alpha + \beta n)$
  - pipeline: pipelined broadcast from each node i, $1 \leq i \leq p$
    $t^{ag} = t^{rs} = 3(p-1)(\alpha + \beta n)$
  - fan-in: gather from other nodes into node i, $1 \leq i \leq p$
    $t^{ag} = t^{rs} \approx 2(p-1)(\alpha + \beta n)$
  - full fan-in: each node i in parallel:
    for each $k = 1 : n$, send data to node $i + k$;
    for each $k = 1 : n$, receive data from node $i - k$;
    $t^{ag} = t^{rs} = \frac{p-1}{o}(\alpha + \beta n)$
    o is degree of overlap on simultaneous receives, $1 \leq o \leq 3$ on Bunyip
- simple to implement; not contention-free;
  but may be fast if there is *overlap* between the sub-operations
  - exact performance models are in terms of $\alpha_s, \alpha_r, \beta_r, \beta_s$

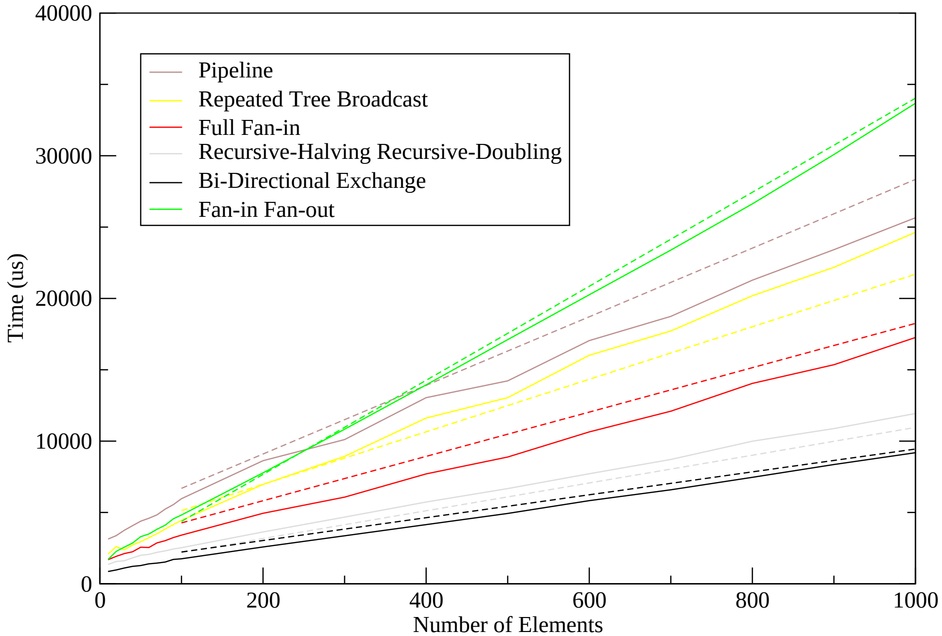
7 Results: comparison of algorithms

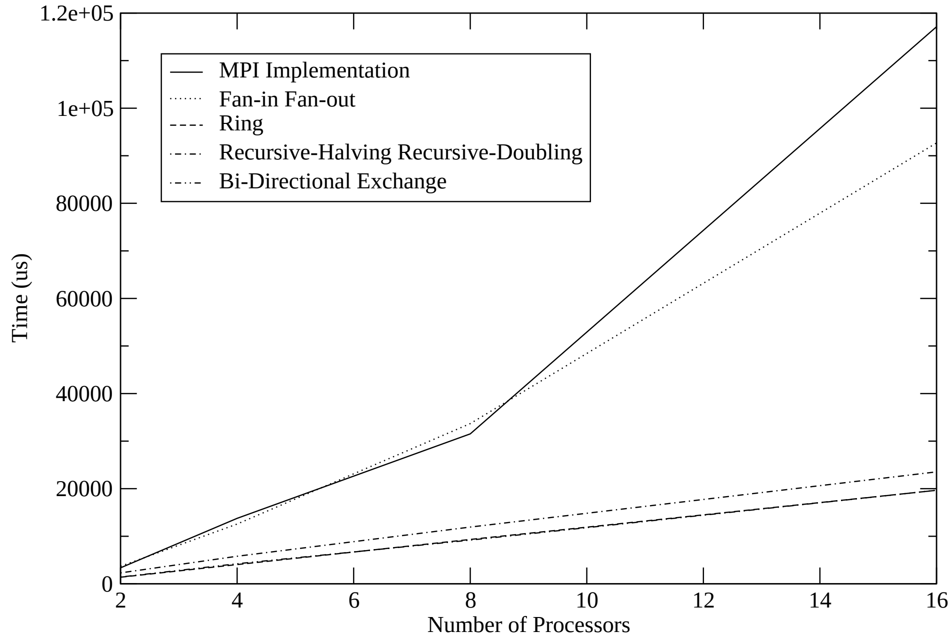




- results for All-Gather (left) & Reduce-Scatter (right), for $p = 8$ (single Bunyip group)
- for All-Reduce, bi-directional exchange was best (as expected), and also significantly faster than MPI
- for $1000 \leq n \leq 10,000$, results were similar except some degradation at $n \geq 8,000$ for ring, fan-in and full fan-in

8 Results: compare with performance models & scalability





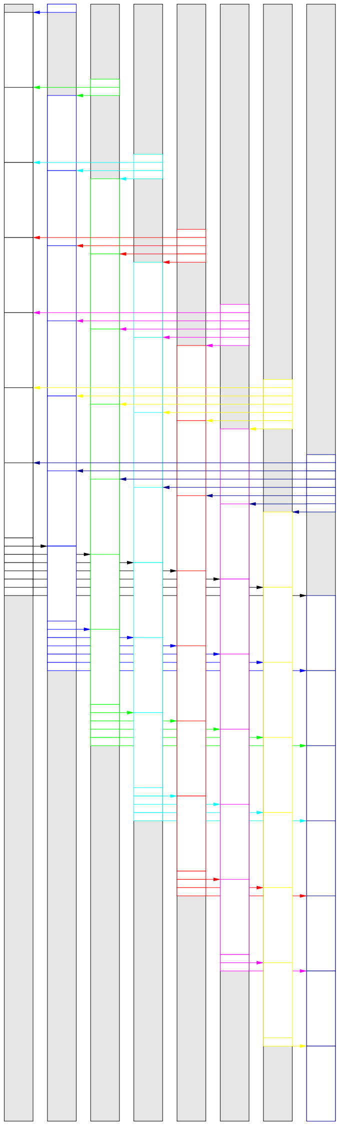
- results for All-Gather: compare with performance models for $p = 8$ (left), and performance at $n = 1000$ (right)
  - close match for all ops, with full-fan-in's overlap factor $o^{ag} \approx 1$, $o^{rs} \approx 1.2$
- larger p requires the operations to be 'inter-group' on the Bunyip:
  - a hierarchical algorithm (based on ring or bi-directional exchange worked $\approx 20\%$ better for $n \geq 1000$
    (can avoid large messages between groups)

9 A Simulator for Collective Communications

- a message simulator and diagramming tool was developed to understand performance overlap
  - generated timing diagrams based on both performance model predictions and actual timestamps for MPI send & receive calls
  - was useful in understanding message overlap effects

    and deriving the performance models for tree and fan-in

    (predicted diagram for fan in, $p = 8$, on right)
- is generic; source code is available from http://cs.anu.edu.au/~Peter.Strazdins/projects/ClusterComm



10 Conclusions

- LAM MPI performance was sub-optimal for these operations
- for clusters like Bunyip
  - bi-directional exchange worked well for small messages, ring slightly better for large
  - significant overlap can occur on algorithms based on repeated sub-operations:
    - required more complex performance models (with separated send and receive components)
    - full fan-in (believed novel) modestly faster for Reduce-Scatter
      - would be even better if overlap factor $o \to 3$
    - these are very simple and reliable to implement
  - close match of actual results with performance models indicate a good understanding of performance is achieved
  - hierarchical algorithms slightly better for ‘inter-group’ communications
- message simulator was a useful tool in understanding performance