This document describes the work completed at the University of California, Santa Cruz under the project “Scalable Internetworking” sponsored by ARPA under Contract No. F19628-93-C-0175. This report covers work performed from 1 April 1993 to 31 December 1995.

Results on routing and multicasting for large-scale internets are summarized. The technical material discussed assumes familiarity with the content of our proposal and previous quarterly reports submitted in this project.
1 INTRODUCTION

Today’s internetworking technology is challenged by growth, the provision of multiple types of services at varying speeds, the support of collaborative environments that require real-time multipoint communications, the control of resources by multiple administrative authorities, and the interoperation of ATM-based internets with connectionless networks and internets. In the long term, providing adequate internet routing that accommodates its size and diversity of service requirements cannot be met with traditional link-state or distance vector routing algorithms, and a strategy is needed for the interconnection of large numbers of connectionless networks through ATM.

Funded by the Advanced Research Projects Agency (ARPA), the University of California, Santa Cruz (UCSC) carried out research on scalable internetworking from 1 April 1993 to 31 December 1995. The original goals of this project were to advance the state of the art in internetworking technology by

- Developing and validating the first new type of routing algorithm (which we call link-vector algorithms or LVA) since the development of the ARPANET’s routing protocols, which introduced the first distance-vector and link-state algorithms for computer networks. LVA implements the selective diffusion of link states based on distributed computation of preferred paths that can take into account service types, policy restrictions, and the characteristics of transmission media.

- Unifying previous work on the correctness of distance-vector and link-state algorithms as a problem of distributed termination detection.

- Developing more efficient mechanisms for termination detection distance-vector and link-state algorithms, which can be used to improve the performance of existing interdomain and intradomain routing protocols.

- Developing new distributed approaches to multicasting capable of supporting multiple types of service within the same multipoint session.

- Applying the new algorithms summarized above, plus novel approaches to the mapping of names into addresses and routes, to the interconnection of connectionless LANs and MANs through ATM-based internets, and to fully-integrated ATM-based internets.

In the course of our research, we developed new ideas on routing and multicasting that we had not predicted as part of our original goals. The results of our research have been made available in the open literature as part of the following 20 publications:

1. F. Bauer and A. Varma, “Degree-Constrained Multicasting in Point-to-Point Networks,” Proceedings of IEEE INFOCOM ’95, April 1995.

2. F. Bauer and A. Varma, “Distributed Algorithms for Multicast Path Setup in Data Networks” IEEE/ACM Transactions on Networking, to appear.
3. F. Bauer and A. Varma, “Distributed Algorithms for Multicast Path Setup in Data Networks,” Proceedings of IEEE GLOBECOM ’95, November 1995.

4. F. Bauer and A. Varma, “ARIES: A Rearrangeable Inexpensive Edge-based On-line Steiner Algorithm,” Proceedings of IEEE INFOCOM ’96, March 1996, to appear.

5. J. Behrens and J.J. Garcia-Luna-Aceves, “Distributed, Scalable Routing Based on Link-State Vectors,” Proc. ACM SIGCOMM 94, London, U.K., August 1994.

6. J.J. Garcia-Luna-Aceves and S. Murthy, A Path-Finding Algorithm for Loop-Free Routing,” accepted for publication in IEEE/ACM Transactions on Networking, 1996.

7. J.J. Garcia-Luna-Aceves and J. Behrens, “Distributed, Scalable Routing based on Vectors of Link States,” IEEE Journal on Selected Areas in Communications, Vol 13, No. 8, October 1995.

8. J.J. Garcia-Luna-Aceves and S. Murthy, “A Loop-Free Path-Finding Algorithm: Specification, Verification and Complexity,” Proc. IEEE INFOCOM 95, Boston, MA, April 1995.

9. J.J. Garcia-Luna-Aceves and Y. Zhang, “Reliable Broadcasting in Dynamic Networks,” Proc. IEEE ICC 96, Dallas, Texas, June 23-27, 1996.

10. L. Kalampoukas, A. Varma, and K. K. Ramakrishnan, “An Efficient Rate Allocation Algorithm for Packet-Switched Networks Providing Max-Min Fairness,” Proc. IFIP Conference on High-Performance Networks (HPN 95), September 1995.

11. L. Kalampoukas, A. Varma and K. K. Ramakrishnan, “Dynamics of an Explicit Rate Allocation Algorithm for Available Bit-Rate (ABR) Service in ATM Networks”, Proc. IFIP Conference on Broadband Networks, Montreal, Canada, April 1996, to appear.

12. L. Kalampoukas and A. Varma, “Analysis of Source Policy in Rate-Controlled ATM Networks,” Proc. ICC ’96, to appear.

13. S. Murthy and J.J. Garcia-Luna-Aceves, “A Routing Protocol for Wireless Networks,” accepted for publication in ACM NOMAD Journal, 1996.

14. S. Murthy and J.J. Garcia-Luna-Aceves, “Congestion-Oriented Shortest-Multipath Routing,” Proc. IEEE INFOCOM 96, San Francisco, California, March 1996.

15. S. Murthy and J.J. Garcia-Luna-Aceves, “A Loop-Free Path-Finding Algorithm: Analysis of Dynamics,” Proc. IEEE Globecom 95, Singapore, November 13–17, 1995.

16. S. Murthy and J.J. Garcia-Luna-Aceves, “A Routing Protocol for Packet-Radio Networks,” Proc. First ACM International Conference on Mobile Computing and Networking, Berkeley, California, November 13–15, 1995.
17. S. Murthy and J.J. Garcia-Luna-Aceves, “A More Efficient Path-Finding Algorithm,” Proc. Twenty-Eighth Annual Asilomar Conference on Signals, Systems and Computers, Pacific Grove, California, October 31- November 2, 1994.

18. S. Murthy and J.J. Garcia-Luna-Aceves, “A Loop-Free Algorithm Based on Predecessor Information,” Proc. Third International Conference on Computer Communications and Networks—ICCCN 94, San Francisco, California, September 11-14, 1994.

19. M. Parsa and J.J. Garcia-Luna-Aceves, “Scalable Internet Multicast Routing,” Proc. ICCCN 95, Las Vegas, Nevada, September 20–23, 1995.

20. Q. Zhu, M. Parsa, and J.J. Garcia-Luna-Aceves, A Source-Based Algorithm for Delay-Constrained Minimum-Cost Multicasting,” Proc. IEEE INFOCOM 95, Boston, MA, April 1995.

All these publications are available online at the following WWW page: http://www.cse.ucsc.edu/research/ccrg/projects.internet.html. A few of our most recent papers are included at the end of this report.

Our results on routing and multicasting are already being applied in other ARPA projects. Specifically, as part of the project Wireless Internet Gateways (WINGS), we are using path-finding algorithms to implement routing protocols for wireless networks.

The rest of this report summarizes the main results of our research. Each section points to the associated publications in the previous list, where the details of our research are presented.

2 ROUTING ALGORITHMS

2.1 Link Vector Algorithms (LVA)

Our results in this area are presented in Publications 5 and 7.

We developed a new type of routing algorithm, which we call link vector algorithm (LVA). The basic idea of LVAs consists of asking each router to report to its neighbors the characteristics of each of the links it uses to reach a destination through one or more preferred paths, and to report to its neighbors which links it has erased from its preferred paths. Using this information, each router constructs a source graph consisting of all the links it uses in the preferred paths to each destination. LVAs ensure that the link-state information maintained at each router corresponds to the link constituency of the preferred paths used by routers in the network or internet. Each router runs a local algorithm or multiple algorithms on its topology table to compute its source graph with the preferred paths to each destination. Such algorithm can be any type of algorithm (e.g., shortest path, maximum-capacity path, policy path) and the only requirements for correct operation are for all routers to use the same algorithm to compute the same type of preferred paths, and that routers report all the links used in all preferred paths obtained. Aggregation of information can take place adapting the area-based routing techniques proposed for DVAs in the past.
Because LVAs propagate link-state information by diffusing link states selectively based on the distributed computation of preferred paths, LVA reduce the communication overhead incurred in traditional LSAs based on flooding of link states. Because LVAs exchange routing information that is related to link (and even node) characteristics, rather than path characteristics, LVAs reduce the combinatorial explosion incurred with any type of DVA for routing under multiple constraints. The simulation results obtained for a particular LVA shows that it has better performance than an ideal link-state algorithm based on flooding and the distributed Bellman-Ford algorithm.

An important contribution of this research was to show that LVAs are correct under different types of routing, assuming that a correct mechanism is used for routers to ascertain which updates are recent or outdated.

LVAs open up a large number of interesting possibilities for internet routing protocols. To name a few, LVAs can be the basis for effective routing protocols based on link-state information for packet radio networks. LVAs can be used to develop more efficient intra-domain routing protocols that are based on link-state information but require no backbones (which eliminates the difficult network-management problems associated with such protocols as OSPF and ISO IS-IS) and can take advantage of aggregation schemes developed for distance-vector algorithms. Finally, LVAs make path-vector algorithms (used in BGP and IDRP, for example) obsolete. LVAs are applicable to the emerging Nimrod architecture and protocols being developed under ARPA sponsorship.

### 2.2 Path-Finding Algorithms

Our results in this area are presented in Publications 6, 8, 13, and 15–18.

Recently, distributed shortest-path algorithms that utilize information regarding the length and second-to-last hop (or predecessor) of the shortest path to each destination have been proposed to eliminate the counting-to-infinity problem of the distributed Bellman-Ford algorithm (DBF), which is used in a number of today’s routing protocols. We call these type of algorithms path-finding algorithms. Although these algorithms provide a marked improvement over DBF, they do not eliminate the possibility of temporary loops. The loop-free algorithms reported to date rely on mechanisms that require routes either to synchronize along multiple hops, or exchange path information that can include all the nodes in the path from source to destination.

We developed the first known path-finding algorithm that is loop-free at every instant. We call this path-finding algorithm the loop-free path-finding algorithm (LPA). According to LPA, update messages are sent only to neighboring nodes. Like previous path-finding algorithms, LPA eliminates the counting-to-infinity problem of DBF using the predecessor information. In addition, LPA eliminates all temporary loops by implementing an internighbor coordination mechanism with which potential temporary loops are blocked before routers can forward data through them. To block a potential temporary loop, a node sends a query to all its neighbors reporting an infinite distance to a destination, before changing its routing table; the node is free to choose a new successor only when it receives the replies from its neighbors. To reduce the communication overhead incurred with internighbor coordination,
nodes use a feasibility condition to limit the number of times when they have to send queries to their neighbors. In contrast to many prior loop-free routing algorithms, queries propagate only one hop in LPA. Furthermore, updates and routing-table entries in LPA require a single node identifier as path information, rather than a variable number of node identifiers as in prior algorithms.

We compared LPA's performance against the performance of the most efficient loop-free algorithm previously known (DUAL) and an ideal link-state algorithm (ILS). The simulation considered the dynamics of these three algorithms after a single event (link or node failure, link or node addition, and link-cost change) and multiple link-cost changes. Our simulation results clearly indicate that LPA is far more scalable than DUAL and ILS. The results obtained for multiple link-cost changes show that LPA is the first distance-vector algorithm to require less overhead traffic than any link-state algorithm based on flooding.

3 CONGESTION-ORIENTED SHORTEST MULTI-PATH ROUTING

Our results in this are are presented in Publication 14.

We have demonstrated that a connectionless routing architecture can provide performance guarantees. We used architectural elements similar to those used in a connection-oriented architecture to allow the network to enforce performance guarantees in the delivery of those datagrams that are accepted into the network.

In our new framework for dynamic multipath routing in connectionless internets, packets are individually routed towards their destinations on a hop by hop basis. A packet intended for a given destination is allowed to enter the network if and only if there is at least one path of routers with enough resources to ensure its delivery within a finite time. In contrast to existing connectionless routing schemes, once a packet is accepted into the network, it is delivered to its destination, unless resource failures prevent it. Each router reserves buffer space for each destination, rather than for each source-destination session as it is customary in a connection-oriented architecture, and forwards a received packet along one of multiple loop-free paths towards the destination. The buffer space and available paths for each destination are updated to adapt to congestion and topology changes.

Parekh and Gallager have analyzed worst-case session delay in a connection-oriented network architecture [12]. We have obtained a similar upper bound on the steady-state delay experienced by a datagram accepted into the network using our new routing framework; this upper bound is given by the following equation:

\[ D_{ij}^*(t) < \Delta_j^i(t)[1 + Q_j^*(t)] + MAD_j^i(t) \] (1)

where \( D_{ij}^* \) is the longest delay that can be experienced by a packet created or forwarded by node \( i \) to destination \( j \) at time \( t \), \( Q_j^*(t) \) is the worst-case delay of transmitting packets already in queue for destination \( j \), and \( MAD_j^i(t) \) is the maximum delay allowed by the routing protocol for any neighbor of node \( i \) to be considered part of a loop-free path to
destination $j$. The first term of Eq. 1 corresponds to the delay incurred by sending all backlogged packets at time $t$ to a neighbor with the longest link propagation delay (which is denoted by $\Delta_i^j(t)$). The second term corresponds to the maximum delay incurred by any neighbor receiving the backlog packets; because any such neighbor must be on the “shortest multipath” from $i$ to destination $j$ (i.e., a set of loop-free paths with a maximum delay smaller than $MAD^j_i(t)$), that delay can be at most equal to $MAD^j_i(t)$.

The above bound is the first known upper bound for packet delays in a connectionless routing architecture, and is possible because datagrams are accepted only if routers have enough credits to ensure their delivery, and datagrams are delivered along loop-free paths. In contrast, in traditional datagram routing architectures, any datagram presented to a router is sent towards the destination, and the paths taken by such datagrams can have loops; therefore, it is not possible to ensure a finite delay for the entry router or any relay router servicing a datagram.

4 INTERNET MULTICASTING

4.1 Delay-Constrained Minimum-Cost Multicasting

Our results in this area are presented in Publication 20.

Different optimization goals can be used in multicast routing algorithms to determine what constitutes a good tree. One such goal is providing minimum delay along the tree, which is important for such multimedia applications as real-time conferencing. Another optimization goal is making use of the network resources as efficiently as possible; two interesting variants of this objective are

- Minimizing the total bandwidth utilization of links; we call this objective utilization driven, because it minimizes the total bandwidth utilization cost of links for a data stream sent from the source to destinations.

- Distributing bandwidth utilization of sessions among links in the tree in order to minimize congestion along links; we call this objective congestion driven, because it minimizes the maximal link cost requirement along the transferring paths.

Previous optimization techniques for multicast routing algorithms have considered the above two optimization objectives, but have treated them as distinct problems. Dijkstra’s shortest path algorithm [4] can be used to generate the shortest paths from the source to destination nodes; this provides the optimal solution for delay optimization. Multicast routing algorithms that perform cost optimization have been based on minimum Steiner tree which is known to be NP-complete problem [6]. Some heuristics for the Steiner tree problem [9,14,18] have been developed that take polynomial time and produce near optimum results. In Kou, Markowsky and Berman’s (KMB) algorithm [9], a network is abstracted to a complete graph consisting of edges that represent the shortest paths among source node and destination nodes. The KMB algorithm applies Prim’s algorithm [13] to construct a
minimum spanning tree in the complete graph, and the Steiner tree of the original network is obtained by achieving the shortest paths represented by edges in the minimum spanning tree. Waxman [20] examined the dynamic update of the tree if destination nodes join or leave the tree occasionally. Shacham and Meditch [17] investigated the maximum flow distribution of multiple streams along a multicast tree; Optimum assignment is based on link capacity and destination requests, but the request is not delay-bounded and a dynamic programming algorithm is devised that may take exponential time complexity.

Bharath-Kumar and Jaffe discuss optimization on both cost and delay [7]. However, they assume that cost and delay functions are identical. Kompella, Pasquale and Polyzos [8] propose two heuristics (which we call the KPP algorithm) that address delay-bounded Steiner trees; the KPP algorithm extends the KMB algorithm by taking into account an integer-valued delay bound in the construction of shortest paths.

We developed a new algorithm for multicast tree construction that we call Bounded Shortest Multicast Algorithm (BSMA). BSMA is source based, which means the source of the multicast is assumed to know all the information needed to construct the multicast tree. Although the model of delay-bounded minimum Steiner tree is similar to the one used in the KPP algorithm, we generalize the formulation of the problem to more realistic network settings; the major contributions of the new algorithm, which we call Bounded Shortest Multicast Algorithm (BSMA) can be summarized as follows:

- It considers the congestion-driven and utilization-driven variants of the cost function.
- It specifies variable delay bounds reserved for destination nodes, that is, different destinations have variable delay bounds; furthermore, a delay bound can take arbitrary real values.
- Instead of using a single pass as in previous algorithms, it iteratively (in multiple passes) minimizes the cost function of the tree.

Instead of the single-pass tree construction approach used in most previous heuristics, BSMA is based on a feasible search optimization method, starting from the minimum-delay tree, and monotonically decreases the cost by iterative refinement of the delay-bounded tree. The optimality of the costs of the delay-bounded trees obtained with BSMA were analyzed by simulation; our results show that, depending on how tight the delay bounds are, the costs of the multicast trees obtained with BSMA are very close to the costs of the trees obtained by a well-known, provably near-optimal minimum Steiner tree heuristic, with the costs within the factor 2(1 − 1/|S|) of the optimal Steiner tree for |S| connected nodes.

4.2 Multicast Internet Protocol (MIP)

Our results in this area are presented in Publication 19 and the following paper:

- M. Parsa, and J.J. Garcia-Luna-Aceves, “A Protocol for Scalable Loop-Free Multicast Routing,” submitted to IEEE Journal on Selected Areas in Communications, 1996.
Multicasting is supported in local area networks (LANs), using hardware technologies. Recently, multicasting has been extended to internetworks by Deering [2]. Based on Deering’s work and built into the TCP/IP protocol suite, the internet group message protocol (IGMP) is used to disseminate multicast membership information to multicast routers. Deering’s method permits routers to figure out dynamically how to forward messages. A delivery tree is constructed on-demand and is data-driven. The tree in the existing IP architecture is the reverse shortest-path tree and shortest-path tree from the source to the group for distance-vector (i.e., DVMRP [19]) and link-state routing (i.e., MOSPF [11]), respectively. For example, the Multicast Backbone (MBone) in today’s Internet consists of a set of routers running DVMRP. However, there are several shortcomings with the existing IP multicast architecture, i.e., DVMRP and MOSPF. First, all routers in the Internet have to periodically generate and process control message for every multicast group, regardless of whether or not they belong to the multicast tree of the group. Thus, routers not on the multicast tree incur memory and processing overhead to construct and maintain the tree for the lifetime of the group. The packets that are periodically flooded throughout the Internet but that do not lead to any receivers or sources consume bandwidth. In DVMRP, it is the data packets that are periodically flooded when the state information for a multicast tree times out. In MOSPF, it is the link-state packets, containing the state information for group membership, that are periodically flooded. Second, the multicast routing information in each router is stored for each source sending to a group. If there are S sources and G groups, the multicast protocols scale as $\Theta(SG)$. Finally, the IP multicast protocols, being extensions of unicast routings, are tightly coupled to the underlying unicast routing algorithm. This complicates inter-domain multicasting if the domains involved use different unicast routing. The unicast routing is also made more complicated by incorporating the multicast-related requirements.

To overcome the above shortcomings, two protocols have been recently proposed: the core-based tree (CBT) architecture [1] and the protocol independent multicast (PIM) architecture [3]. Although both approaches constitute a substantial improvement over the current multicast architecture, each protocol has its own limitations. A main limitation of CBT is that it constructs only a single tree per group and thus provides longer end-to-end delays than would be obtained along a shortest-path tree. A main limitation of PIM is that the periodic control messages, i.e., its soft-state mechanism, incur overhead even in a stable internet. We have shown that both protocols suffer from temporary loops resulting from the use of inconsistent unicast routing information, and neither protocol has been verified to provide correct multicast routing trees after network changes.

We developed a new multicast routing protocol called Multicast Internet Protocol (MIP), which solves the shortcomings of the previous approaches to multicast routing. MIP offers a simple and flexible approach to the construction of both group-shared and shortest-path multicast trees. The shortest-path trees in MIP can be relaxed to cost-bounded trees, making it possible to trade off optimality of the tree with the control message overhead of maintaining a shortest-path tree. MIP accommodates sender-initiated and receiver-initiated multicast tree construction, which makes MIP flexible to use for a wide range of applications with different characteristics, group dynamics and sizes. Although MIP is independent of the
underlying unicast routing, MIP never creates loops in a multicast tree. Since applications for group communication tend to be bandwidth intensive, for example, from using images and video, loop-freedom is a specially important consideration in multicasting. Instead of using the idea of “soft state” to maintain multicast routing information, MIP uses diffusing computations to update and disseminate multicast routing information and to insure loop-freedom. This last feature of MIP has a number of scaling properties: under stable network conditions, MIP has no control message overhead to maintain multicast routing information; MIP responds to network events as fast as routers can propagate update information, rather than waiting for timers to expire before propagating changes; finally, because no loops can occur, routers obtain correct multicast routing or stop forwarding data to a portion of a multicast tree as fast as update information can propagate along a desired multicast tree.

5 RELIABLE BROADCASTING

Our results in this area are presented in Publication 9.

Network broadcasting consists of delivering copies of the same message to all the nodes in a network. The information that is to be broadcasted can be varied, for example, a command, the information of users’ location, the information about users’ connectivity, or a network topology change due to link failures and repairs. The focus of this paper is on the reliable broadcasting of information in wireless networks with dynamic topologies.

Reliable broadcasting is not trivial when the topology of the network can change due to failure or mobility, whether or not the source of information has a local copy of the topology. A reliable broadcast protocol must ensure that the information from the source node reaches all the nodes that are connected to the source node in the network within a finite time, and that the source node is notified about that. A reliable broadcast protocol for dynamic networks should

- Operate independently of the routing information available at nodes, which may be inaccurate, and without requiring the source to know which nodes have a physical path to it
- Incur low latency and as few messages as possible in order to broadcast a message from any given source.

Surprisingly, little work exists on reliable broadcast protocols in dynamic networks; most broadcast protocols proposed in the past (e.g., [15], [16]) are based on what Segall calls the propagation of information (PI) protocol and the propagation of information with feedback protocol (PIF) [16]. PI is basic flooding; it starts by the source node sending a message containing the information to all its neighbors, and each other node in the network sends a similar message to its own neighbors when it receives the first such message. PIF is based on PI, with the source node being informed when the information has reached all connected nodes in the network. The difference between PIF and PI is that, when a node \( i \) receives the first message from a neighbor node \( p_i \), node \( i \) labels that neighbor node as its successor.
When a node $i$ other than the source has received the source’s message from all neighbors, it sends the source’s message back to its successor $p_i$. PIF terminates when the source node receives its own message from all its neighbors.

All reliable broadcast protocols based on flooding that have been proposed for dynamic topologies in the past (e.g., [15]) are based on the routing protocol by Merlin and Segall [10]. These protocols proceed in cycles triggered and terminating at the source of the message. A cycle consists of two phases. First, the message propagates one additional hop away from the source, then acknowledgments to the message propagate towards the source. The source starts by sending a message that is acknowledged by all its neighbors. When the source receives the acknowledgments from its neighbors, it then resends the message asking the neighbors to propagate the message one more hop to their own neighbors. The neighbors forward the message to their neighbors and send their acknowledgments back to the source when they receive the acknowledgments from all their own neighbors, and so forth. This scheme incurs too much communication overhead to be attractive for a wireless network; furthermore, an implicit assumption of this approach is that a node can have a fairly stable successor to the source, which does not apply in a network with mobile nodes.

We developed a new reliable broadcast protocol that is correct for both static and dynamic networks. We call this protocol the reliable broadcast protocol (RBP).

RBP ensures that every node connected to the source node receives the information from the source node at least once, and that the source node is positively informed that the information reaches all the connected nodes in the network within a finite time. RBP works in a similar way to PIF for the case of a static network. However, in contrast to prior approaches of reliable broadcasting in dynamic networks, our proposed protocol requires the source to send each broadcast message only once, and diffusing computations [5] are used to eliminate the need for the source node to control the propagation of information in multiple rounds. An important contribution of this paper is the adaptation of Dijkstra and Scholten’s basic scheme to dynamic topologies. Instead of defining a single successor for each node in a directed acyclic graph (DAG), RBP permits each node to define a successor set formed with all those neighbors who transmit the source’s message. To our knowledge, RBP is the first protocol for reliable broadcasting that is not based on PIF or pre-established trees.

6 MULTICASTING IN ATM NETWORKS

Our results in this area are presented in Publications 1–4.

We developed and evaluated a number of heuristic algorithms for finding efficient multicast trees in the presence of constraints on the copying ability of the individual switch nodes in an ATM network. We studied both centralized and distributed heuristics for solution of the degree-constrained Steiner problem. Two distinct approaches were considered for the design of distributed DCSP heuristics. The first approach involves design of distributed versions of centralized DCSP algorithms. We introduced distributed versions of two DCSP heuristics, SPH and K-SPH. The second approach is to modify the solution obtained from an unconstrained heuristic to satisfy the degree constraints using a distributed post-processing
algorithm. We compared the algorithms by simulation based on three criteria: quality of solution, convergence time, and the number of unsolved networks. Our results show that each of the heuristics generated degree-constrained multicast trees within 10% of the best solution found. Surprisingly few test networks were unsolvable. The distributed post-processing heuristic presented is of particular interest since it may be used with any Steiner heuristic. When paired with a good unconstrained distributed Steiner heuristic, it gave away little quality of solution while converging rapidly.

We introduced and evaluated a new heuristic, ARIES, for updating multicast trees dynamically in large point-to-point networks. The algorithm is based on monitoring the accumulated damage to the multicast tree within local regions of the tree as nodes are added and deleted, and triggering a rearrangement when the number of changes within a connected subtree crosses a set threshold. We derived an analytical upper-bound on the competitiveness of the algorithm. We have also obtained simulation results to compare the average-case performance of the algorithm with two other known algorithms for the dynamic multicast problem, GREEDY and EBA (Edge-Bounded Algorithm). Our results show that ARIES provides the best balance among competitiveness, computational effort, and changes in the multicast tree after each update.

7  CONGESTION CONTROL IN ATM NETWORKS

Our results in this area are presented in Publications 10–12.

Several congestion-control approaches for support of Available-Bit-Rate (ABR) traffic in ATM networks have been proposed recently. These include packet discard schemes, link-level flow control, and rate control with explicit congestion notification, and explicit rate setting. The ATM Forum Traffic Management Committee has been working on a rate-based approach with explicit rate setting as the basis of its congestion-control standards for supporting ABR service.

The rate-based approach requires an algorithm for fair allocation of bandwidth among the connections sharing a common output link of a switch. We designed such an algorithm for rate allocation within the individual switches of an ATM network implementing a rate-based congestion control algorithm for best-effort traffic. The algorithm performs an allocation in $\Theta(1)$ time, allowing it to be applied to ATM switches carrying a large number of virtual channels. When the total available capacity or the requests of the individual connections change, the algorithm is shown to converge to the max-min allocation. The worst-case convergence time is $O(M(2D + \frac{1}{R}))$, where $D$ is the round-trip delay, $M$ is the number of distinct values in the max-min allocation, and $R$ is the rate at which resource-management (RM) cells are transmitted by each source. A patent application on the rate allocation method was filed during last summer.

Since then, we have studied the dynamics of the rate allocation algorithm in various network configurations, and demonstrated that the allocation algorithm is fair and maintains network efficiency in a variety of network configurations. We also studied the behavior of TCP/IP sources using ABR service in a network of switches employing the rate allocation
algorithm; the results show substantial improvements in fairness and efficiency in comparison with the performance of TCP on an underlying datagram-based network. Even in a dynamic network configuration with frequent opening and closing of ABR connections, TCP connections were able to make sustained progress with a switch buffer size as small as 1 Kbyte, providing an average link utilization of approximately 60% of the attainable maximum. We also studied the performance of ABR traffic in the presence of higher-priority variable bitrate (VBR) video traffic and showed that the overall system achieves high utilization with modest queue sizes in the switches, and the ABR flows adapt to the available rate in a fairly short interval. These results are summarized in Reference [2].

We also analyzed the behavior of the source policy in the rate-based congestion control algorithm being developed by the ATM Forum and derived approximate analytical closed-form expressions to describe the rate-increase process. These approximations are used to analyze the impact of the source algorithm on the TCP slow-start process operating over a rate-controlled ATM network where rate allocation is performed explicitly in the switches. The results show that the increase in TCP congestion window ramp-up time is noticeable when the round-trip delay is small. When an idle-detection policy is enabled at the source, the slow-start process is significantly prolonged, and results in slower recovery upon a cell loss. The results are verified by simulation. Reference [3] contains a summary of this work.

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