A Survey of Application-Layer Multicast Protocols

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***Abstract*- In light of the slow deployment of IP Multicast technology on the global Internet and the explosive popularity of peer-to-peer file-sharing applications, there has been a flurry of research activities investigating the feasibility of implementing multicasting capability at the application layer, referred to as Application Layer Multicasting (ALM), and numerous algorithms and protocols have been proposed. This article aims to provide researchers in the field with an understanding of ALM protocols by identifying significant characteristics, from both application requirements and networking points of view, and by using those characteristics as a basis for organizing the protocols into an integrated and well-structured format. Current trends and directions for further research are also presented. This article surveys the literature over the period 1995-2005 on different application layer multicasting approaches.**

Keywords: Internet Multicasting, Application Layer Multicasting, Peer-to-Peer Communications, Multicast Routing.

I. INTRODUCTION

The Internet was designed for and grew primarily due to the success of one-to-one applications such as reliable file transfer and electronic mail. Its growth however has fostered the emergence of new applications that are inherently one-to-many, such as video-on-demand and live media streaming; or many-to-many, such as video conferencing and multiplayer games. These applications put a strain on the available resources and make inefficient use of a one-to-one or in other words unicast-only infrastructure. The need for efficient support of one-to-many and many-to-many applications led to the proposal for the implementation of multicasting on the global inter-network called IP Multicast [12]. In essence, an IP Multicast capable network allows one or more sources to efficiently send data to a group of recipients [12] whereby the source transmits only one copy of the data and the appropriate network nodes efficiently make duplicate copies for each receiver. After a decade of research into the various issues of IP Multicasting such as routing, group management, address allocation, authorization and security, Quality of Service (QoS) and scalability, the widespread deployment of IP Multicast on the global inter-network has been dogged by technical, administrative and business related issues [14]. This is especially true with respect to Internet connections to homes provided by local Internet Service Providers (ISP) that very rarely allow home users the ability to be a part of an IP Multicast session. Therefore there have been recent proposals to alternative group communication services that either grow out of the IP Multicast model and still support IP Multicasting or offer a competing model. El-Sayed et al give a survey of such proposals [17] where they present a survey of multicasting approaches alternative to classic IP Multicasting. These include using reflectors, permanent tunneling (e.g. MBONE), relying on specific routing services such as IPv6, and Application Layer Multicasting or automatic tunneling. In contrast to the general overview of all IP multicast alternatives presented in [17], our paper's contribution is its survey on Application Layer Multicasting specifically and providing much greater details about existing trends and a much deeper discussion of ALM protocols. The motivation behind studying ALM, as opposed to the other proposed alternatives to IP Multicasting, is ALM's practical success and deployability on today's Internet, specially for home users, as demonstrated by file sharing applications such as Napster and Kazaa. Our approach here is to identify properties that are significant across the board for all applications and characterize the protocol architecture accordingly. These properties include application domain, group configuration, routing protocols, and other characteristics that typically lead to trade-offs in design decisions such as mesh-first approach versus tree-first approach (group management), minimum spanning tree or clustering structure (routing), multi-source versus single source (application domain), and many other characteristics. Our paper further contributes to the field by using the above-mention properties for categorizing ALM protocols based on these properties. As such, we define two sets of categorization. In one set, we first classify routing algorithms and their properties and then categorize the protocols based on the type of routing algorithm used. In the second set, we categorize the protocols based primarily on their application domain and group configuration, also taking into account other important characteristics. We begin our discussion with a background about multicasting.

A. Multicasting Background

In one-to-many or many-to-many communications, often a sender may need to send the same message to many receivers. Examples include audio webcasting, where the same audio stream is sent to many receivers and video conferencing or online gaming where any participant can generate data (audio, video, update messages) that need to be sent to all other participants. Traditional approaches such as using multiple one-to-one unicast connections or using a client-server approach are not scalable and will become bottlenecks and eventually collapse with increasing number of users in the system. Multicasting, on the other hand, allows a sender to send the message only once; the network would then deliver the message to all receivers in the group. The source sends a packet to the network, and the network copies the packet at the routers such that each destination will receive a copy of the packet. This approach, which is the main component of IP Multicast [12] will make the most efficient use of network resources compared to one-to-one or client-server approaches, where the packet has to be sent more than once either by the source or by a server. However, this also implies that the network has to be intelligent, in the sense that it has to know how to route the packet such that each destination receives a copy. In other words, the routers in the network must be capable of setting up and tearing down of IP Multicast sessions as well as processing and routing IP Multicast packets. It is this intelligence required from the network that can present a major hurdle in the way of the deployment of IP Multicast in a global inter-network that was originally conceived based on unicasting principals.

Hence, Multicasting requires route establishment since data is forwarded to a group of receivers rather than to individual receivers. Multicast routing protocols come up with solutions to setup routes within the network. A good understanding of this concept is essential to the fundamentals presented in this paper; hence we present an example here to illustrate a typical multicast routing technique: Distance Vector Multicast Routing Protocol (DVMRP) [65]. DVMRP is a multicast extension to the unicast routing concepts used in RIP (Routing Information Protocol) [81]. It is a source-based routing protocol where the receiver initiates the calculation of routing information. Therefore, a spanning tree, optimal with respect to delay, is created for each source. Multicast data units are then routed using reverse path multicasting (RPM). It applies techniques like poison-reverse and graft data units for dynamic control of the multicast tree. Figure 1(a) represents a network consisting of a set of routers *A* to *E*. A cost is associated with each link interconnecting two routers. The number associated with the cost is an indication of the value of parameters such as end to end delay, maximum outgoing bandwidth, or any other parameter pertinent to the application (actual $ cost, out degree, …), and should be considered as a normalized number that is relative across all links. For instance, in Figure 1(a), the link from A to C is more "costly" than the link from C to D. A number of multicast group members (r1, r2, r3, r4) are attached to some of the routers. In a real application, these could be home users participating in an online game, for example. DVMRP builds a separate shortest path for each sender. For example, in Figure 1(a), there is more than one path from Router A to Router D: A-D and A-C-D. The cost of the first path (18) is higher than that of the second path (8+5=13). Figure 1(b) shows the shortest path from source S, attached at Router A, to receiver r1. Similarly, when receiver r2, r3 and r4 join the system in that order, the tree is further extended as shown in Figure 1(c), 1(d) and Figure 1(e), respectively. Figure 1(e) clearly shows the data distribution tree among the multicast members from the source attached at Router A. It should be noted that this tree is only for the single source S. When dealing with multiple sources, the tree construction becomes more complicated, as we shall see later in the article.

In addition to the approach shown in the above example, there are other approaches for multicast routing. Multicast extension to the unicast OSPF, called MOSPF, is another routing protocol for IP multicasting [66]. It is based on OSPF (Open Shortest Path First) [82] and can be categorized as a source based algorithm. In contrast to DVMRP, it is not a reverse path algorithm, and is based on link state algorithm. Core-based trees (CBT), another approach, use the concept of shared trees with rendezvous points [67][68]. CBTs generate a shared bidirectional multicast tree that take into account the current group membership when it is being established. The main objective of CBT is to minimize the amount of status information and to reduce the control overhead. But it has the disadvantages of traffic concentration and non-optimal paths. Protocol Independent Multicasting (PIM) is yet another approach. PIM has two variants: PIM-sparse mode [69] and PIM-dense mode [70]. These modes are inherently two different multicast routing protocols. They operate efficiently for sparse and dense groups respectively. In PIM-sparse mode, it assumes that nodes are likely to be located far away from each other. The available bandwidth tends to be small. For PIM-dense mode, the distances between members must be short and their availability is judged to be high.

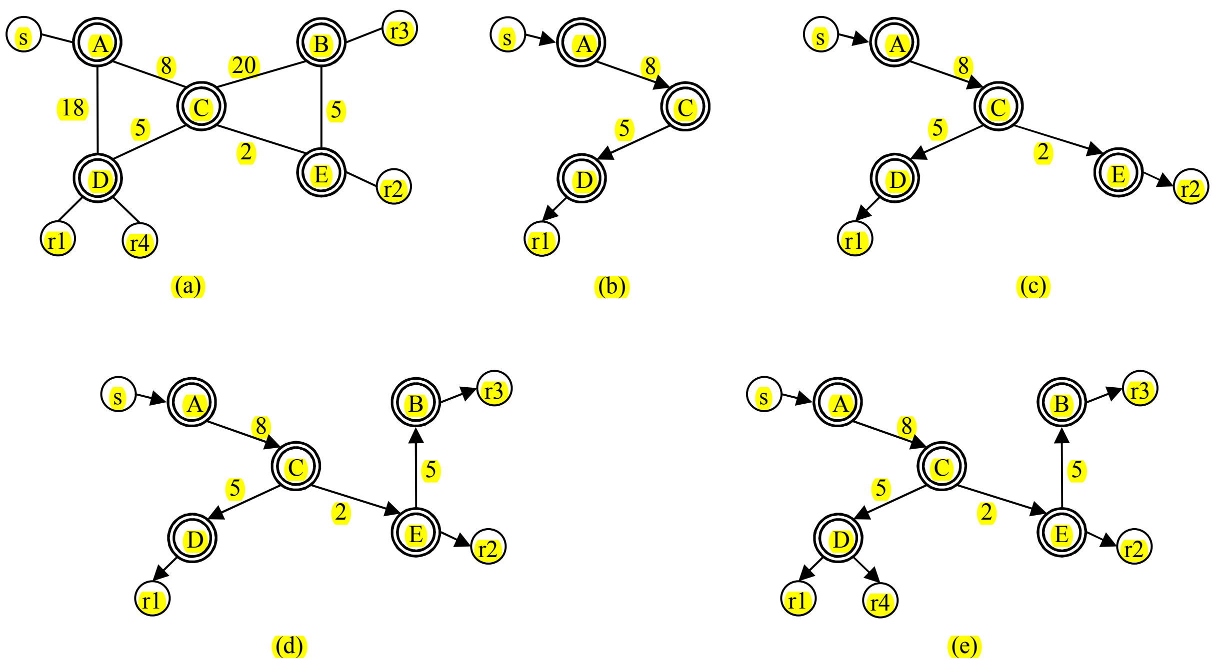


Figure 1. (a) A multicast scenario (b) receiver r1 joins (c) receiver r2 joins (d) receiver r3 joins (e) receiver r4 joins

B. Deployment Issues with Multicasting

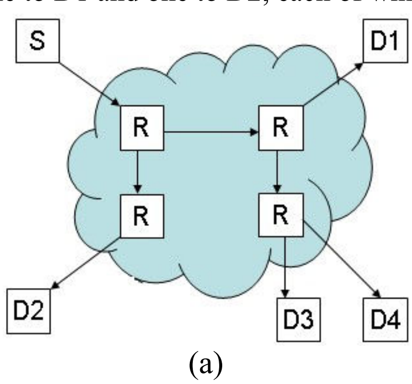
Although IP Multicasting seems to hold great promise, its practical deployment issues have prevented it from becoming available on a global Internet level. Here we briefly describe some of these issues and refer the readers to [14] for a comprehensive list of deployment issues and their detailed discussion.

IP Multicast-capable routers need to be installed at all levels of the network (from backbone to edge routers) for the multicasting service to work and be widely available, presenting a substantial cost to ISPs. In addition, there is a tendency to install simple and unintelligent (therefore very fast) routers at the backbone level since they can more efficiently handle high capacity traffic instead of routers that can handle complex services such as IP Multicasting. There also exist management and security issues related to the deployment of IP Multicast: the ease of flooding attacks via multicasting, unauthorized reception of data from a multicast session, preventing allocation of same multicast address for two sessions, the difficulty of setting up firewalls while allowing multicasting, etc. Billing and service charge is another problem: a standard model to charge for the delivery of packets duplicated by routers does not yet exist. Note that most of the problems discussed above are easier to solve in an Intranet environment controlled by a single entity due to the level of control that exists in an Intranet. However, when it comes to the Internet, these issues become problematic to the extent that they make the deployment of IP Multicast at all levels of the Internet next to impractical. In fact other approaches, such as the Multicast Backbone (MBONE) [83] project of the mid 90's bring multicasting closer to reality. In essence, MBONE uses unicast connections between two or more subnetworks which are capable of IP Multicast, referred to as Multicast Capable Islands, by encapsulating the multicast packet in a regular unicast IP packet and sending it from one subnetwork to others. This technique is also known as IP tunneling. But, inherent to the MBONE are the general problems of IP Multicasting such as receiver authentication, group management and possibility of flooding. In addition, the static setting up of unicast tunnels stymies the natural growth of such a network and assumes responsible use of the available resources. Consequently, the MBONE is not made available to typical home Internet users through their ISPs, restricting its use among education and research institutions.

The lack of network-level support for multicasting has thus led researchers and commercial entities to seek alternative ways of multicasting at the application layer. In this article we present the rational and design concepts behind ALM. We will compare it against IP multicasting and discuss its pros and cons. A novel classification of various ALM protocols for the past 10 years is also presented. This classification, structured in 2 sets of categorization based on application configuration and routing algorithm type, gives a unique perspective of the plethora of ALM protocols that have emerged, helping practitioners in the field select suitable protocols for their given multi-user networked applications. We will also take a closer look at three popular ALM protocols (ZIGZAG [44], NICE [3], and OMNI [4]) and present their inner working as a tutorial for those researchers who are interested in developing their own ALM protocol for a specific application. The rest of this article is organized as follows: Section II gives an introduction to ALM and compares it to IP Multicasting, while Section III discusses design of ALM protocols. In Section IV, we present the classification of various ALM protocols. Some classical ALM protocols are explained in Section V. Section VI portrays open issues and future work. Finally, Section VII concludes the paper with closing remarks.

II. APPLICATION LAYER MULTICASTING

The concept of ALM is simply the implementation of multicasting functionality as an application service instead of a network service. Figure 2(b) represents the ALM configuration for the same group of sender and receivers in the IP multicasting scenario shown in Figure 2(a). Here, the multicasting tree has been built at the application layer. Using only the unicasting capability of the network, the source sends two packets, one to D1 and one to D2, each of which in turn send the packet to D4 and D3, respectively.



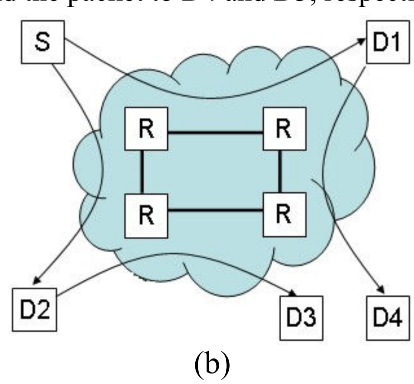


Figure 2. (a) IP multicasting scenario (b) Application layer multicast

While IP Multicast is implemented by network nodes (i.e. routers) and avoids multiple copies of the same packet on the same link as well as possibly constructing optimal trees, ALM is implemented by application nodes (either end systems or proxies) and results in multiple copies of the same packet on the same link as well as typically constructing non-optimal trees. In exchange for its inefficiency, as compared to IP Multicast (by resulting in higher stress links and larger diameter trees), ALM remedies the key shortcoming of the IP Multicast model: easier and possibly immediate deployment over the Wide Area Network. For example, End System Multicast (ESM) [8][10], one of the current implementation of ALM, has been already deployed successfully on the Internet in various applications. In ESM, when a user tunes into the system, this end-host is both downloading the data and uploading it to other end-host.

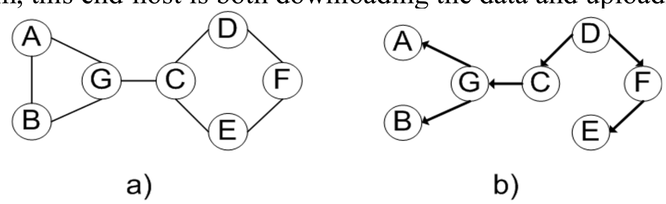


Figure 3. Sample overlay topology b) an overlay multicast tree

In what can be regarded as one of the key efforts advocating ALM, Chu et al. illustrated using both simulation and Internet experiments that ALM systems can form overlay multicast trees that incur low performance penalties (in terms of link stress and tree stretch) compared to IP Multicast [10]. ALM disadvantages such as longer delays and less efficient network usage compared to IP multicasting are balanced by its advantages such as immediate deployability on the Internet, easier maintenance and update of the algorithm, and last but certainly not least the ability to adapt to a specific application. A common approach to Application Layer Multicasting is for the multicast participants to establish an overlay topology of unicast links to serve as a virtual network (overlay network) on top of which multicast trees can be constructed. Figure 3 below shows an example of 7 peers forming a topology (Figure 3(a)) and a multicast tree being constructed with node D as the source (Figure 3b).

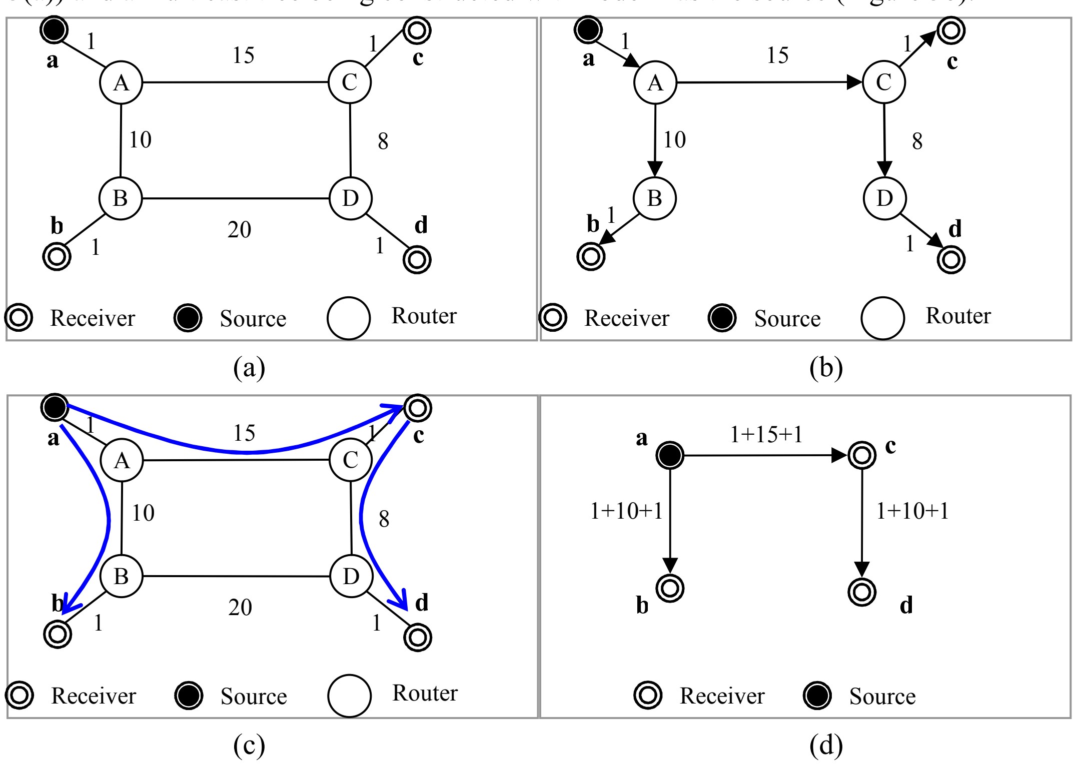


Figure 4. A physical topology (b) IP multicast tree constructed by DVMRP (c) ALM concept (d) End-system overlay network

To better illustrate the performance penalties mentioned above, let us have a closer look at one scenario comparing IP Multicast and ALM. Consider Figure 4(a) that shows a physical topology. There are four routers (A-D), and four end-systems (a-d). Link delays are as indicated. Assume ‘a’ wishes to send data to all other end-systems. Figure 4(b) depicts the IP Multicast tree constructed by DVMRP. Routers A and C receive a single copy of the packet and forward it along multiple interfaces. At most one copy of a packet is sent over any physical link. Each recipient receives data with the same delay as though End-system ‘a’ were sending to it directly by unicast. ALM on the other hand does not rely on router support for multicast. Here, data replication and forwarding are handled by the end-systems as shown in Figure 4(c). Figure 4(d) shows how end-system overlay network maps onto the underlying physical network. The resource usage for IP multicast and ALM for this particular case are 37 and 39 respectively. ALM is therefore more “costly” in this example, again balanced with the benefit of being immediately deployable.

Multicast routing protocols build multicast trees to deliver data and to exchange necessary routing information. In IP multicast, each host informs to its designated multicast router in its subnetwork when it joins or leaves the group. Then the multicast routers exchange group membership information over the multicast tree. All of this control overhead about members joining, members leaving, and updating the multicast tree is carried by the Internet Group Membership Protocol (IGMP) [85]. As there is no redundant path in the tree delivery structure, IP multicast improves network efficiency and scales to a large group size. Despite its bandwidth efficiency, it suffers from the deployment issues mentioned earlier. Application layer multicast, although less efficient than IP Multicast as demonstrated in the above comparison, is receiving increasing popularity in the multicast community primarily due to its ease of deployment. In ALM, multicast architecture, group membership, multicast delivery structure construction, and data forwarding are exclusively controlled by participating end hosts, thus it does not require the support of intermediate nodes such as routers. On the negative side, an end-host in ALM has little or no knowledge about the underlying network topology, thus resulting in performance penalty in term of longer end-to-end latency and lower efficiency compared to IP multicast. Group membership and multicast delivery structures and monitoring of network conditions are also done at end hosts, causing additional overhead for end hosts compared to IP multicasting. Table 1 below is a conceptual comparison of typical IP multicast with ALM.

Table 1. Conceptual Comparison of IP multicast and ALM

Issues	IP multicast	Application Layer Multicast
Multicast efficiency in terms of delay/bandwidth	High	Low - Medium
Complexity or Overhead	Low	Medium - High
Ease of deployment	Low	Medium – High
The OSI layer where the multicast protocol works	Network layer	Application layer

In ALM, new members find out about the topology from a common bootstrap point called a Rendezvous Point (RP) and join the topology by exchanging control messages with a subset of members already part of the topology. Unlike the IGMP protocol used in IP Multicasting, the control messages in ALM are exchanged in an application-specific manner and are completely up to the designers of the protocol. A ‘good’ topology consists of a rich connected graph, such that a peer is connected to other peers through multiple paths, and in an efficient and cost-aware manner, such that the distance or delay between peers is minimized while the number of connections is bounded. Other metrics such as robustness (ability to deal with members leaving the topology), scalability (ability to efficiently increase the size of the topologies for very large number of peers) and low control overhead (minimizing the exchange of control messages) also determine the quality of an overlay topology. Creating and maintaining ‘good’ topologies thus becomes one of the core responsibilities of an ALM protocol. Once a topology is constructed and maintained, a multicast tree can be constructed on top of the graph according to a routing strategy that would commonly strive to minimize the cost of the multicast tree in terms of the delay (or other important parameters, depending on the application) experienced by each peer as well as the amount of data duplication each peer is required to perform. Revisiting Figure 3, we can say that

Figure 3b shows an example of overlay tree over the sample topology of Figure 3a. In the next section, we will take a closer look at these design issues pertaining to the ALM topology and multicast tree.

III. APPLICATION LAYER MULTICAST PROTOCOL DESIGN

Since its introduction, there have been a myriad of ALM protocols with a wide variety of approaches and characteristics. Designing a protocol typically involves making design decisions based on a given set of requirement, constraints under certain circumstances and given set of resources whose availability is assumed. The aim of this section is to highlight some of the more important categories and general approaches of the different protocols based on these requirements, constraints and assumed resources and discuss how they affect the service each protocol provides as well as how its overall characteristics.

A. Application Domain

Perhaps the most crucial feature of an ALM protocol and one that affects most of its resulting characteristics is its targeting application. The application domain determines the number of users that a protocol must support, the data types a protocol's delivery tree must accommodate and the metrics that such a tree attempts to optimize. We follow the same categorization of application domains driving multicast deployment as those according to Diot et al. [14]:

1. **Audio/video streaming:** usually involves a single source distributing media to a large number of receivers. Examples include live streaming of a sporting event, or streaming of pre-recorded news. The primary metric is bandwidth and latency to a lesser extent
2. **Audio/video conferencing:** these involve small to medium size groups interacting in a multi-party conferencing session. The difference with the previous category is the smaller group size, higher degree of interactivity and the existence of multiple sources. Both bandwidth and latency are important metrics
3. **Generic multicast service:** protocols falling into this application domain category try to create a generic multicast service based on specific metrics that can affect a variety of applications
4. **Reliable data broadcast and file transfer:** reliable transfer and distribution of (usually large) files (e.g. distributed databases and file sharing). Bandwidth is the only metric

As can be seen, the different classes of applications have different sets of requirements regarding reliability, latency, bandwidth, and scaling. Such requirements in turn determine the design choices of ALM protocol regarding the group management mechanism it deploys. The application domain therefore influences the ALM protocol. In a tree based multicast system, for example, a node is either an interior node (has children) or a leaf node (has no children). This design choice initiates two problems. First, it is an unfair system. Only the interior nodes are responsible to forward the data. The system becomes unbalanced as leaf nodes increase more rapidly than the interior nodes. Second, due to network capacity, interior nodes may not handle high bandwidth applications – sacrificing the quality. In an application level streaming system, usually audio/video streams are split into several smaller streams. Each stream is stamped with a numerical sequence number to put it at the correct sequence for playback. Usually FEC (forward error correction) code is used to ensure guaranteed stream delivery. For example, split stream [5] ensures that the majority of nodes are interior nodes in one tree, and they will be leaf nodes in all other trees. Hence the system distributes forwarding workloads among all nodes and solves the unfair and unbalanced problem in the conventional streaming system. In split stream, nodes choose to join a subset of the stripes to control their inbound bandwidths and also opt to limit the number of children nodes they accept to control their outbound bandwidths. Thus, it accommodates nodes with different bandwidths and solves the second problem. Similarly, other application domains have different objectives and different constraints. Typically, an ALM protocol focuses on optimizing its tree for a single and very specific application domain.

B. Deployment Level

A key factor determining the set of assumptions an ALM protocol operates based on, is at what level the protocol is expected to be deployed: at the infrastructure level or end system level. Infrastructure-level, also known as proxy-based ALM protocols, requires the deployment of dedicated servers/proxies on the Internet where they self-organize into an overlay network and provides a transparent multicast service to the end-user (Figure 5(a)). End system level ALM protocols on the other hand, assume only a unicast service from the infrastructure and expect end-system hosts to participate in providing the multicasting functionality by taking on some of the forwarding responsibility (Figure 5(b)). Figure 5 highlights the difference between the two approaches to ALM.

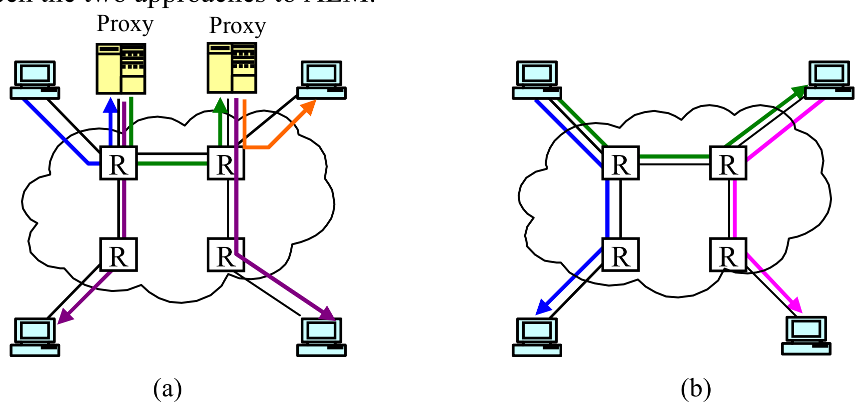


Figure 5. (a) Proxy-based deployment of ALM (b) End-system ALM

The choice between developing an infrastructure level or an end system level ALM protocol is perhaps driven as much by business and marketing issues as purely technological ones. End systems sharing the forwarding load of a multicast session use the existing Internet infrastructure available to them and may not be expected to pay more for participating in the multicast session (as illustrated by the free nature of peer-to-peer file-transfer applications). An infrastructure of dedicated proxies deployed over the Internet that offer multicasting services however are more likely to expect a service charge. There are however technological consequences of a choice between a proxy-based or an end system level approach to ALM.

Proxy-based ALM protocols can take advantage of existing IP Multicast 'islands' by including a representative of an island as an overlay node (and therefore increase their efficiency), can assume greater bandwidth availability to the proxy nodes (compared to the bandwidth available to end-systems), can assume longer life cycle of overlay nodes (compared to transient nature of end systems), relieve end-systems from any forwarding responsibility and therefore reduce application complexity since multicast is transparently made available to end-systems. The major disadvantage of this approach is the need for the deployment of dedicated proxies over the inter-network and so incurring the cost associated with acquiring and deploying them. Proxy-based ALM may also be less adaptable to and less optimized for specific applications since it would typically provide a generic multicast service rather than a service specific to a particular class of applications.

End system ALM protocols enjoy more flexibility, adaptability to specific application domains and immediate deployment over the Internet but may not scale well (to large number of users or large number of simultaneous sessions), must deal with limited bandwidth of end systems and require end systems to take on some of the forwarding responsibility (and therefore increase application software development complexity).

C. Group Management

Once application domain and deployment level has been decided, a protocol designer must make some key decisions regarding how to manage a group of nodes in a multicast session. This includes

1- Basic group management: how users find out about multicast sessions, how they join a session (through a Rendezvous Point, or if p2p substrate is required and some form of flooding is used to find the appropriate source), how they leave (depending on how permanent and cooperative the users are assumed to be), can the users still contribute to existing multicast session even if they are not a part of them? Are they assumed to be very transient and anonymous or more permanent and known users?

2- Whether the management of the group is done in a centralized or distributed way and how this affects the design and service provided.

3- Whether a mesh-first approach or a tree-first approach is taken? What are the advantages and disadvantages of each? If a mesh-first approach is chosen, whether a peer to peer substrate is assumed to exist and if so, what type of substrate with what requirements and services does it provide?

4- Whether the protocol will take advantage of existing IP Multicast islands in order to alleviate part of the multicasting load? If so, how they will interface to these islands?

5- Depending on the assumed life-time of the multicast sessions, whether it is necessary to refine the multicast tree to improve performance as well as deal with fluctuations in the network resources available and deal with congestion? If so, how aggressive these refinement methodologies can be with its effects on the stability of the system and the service provided to users

The basic group management services that an ALM protocol provides consists of a mechanism for the new nodes to discover a multicast session (typically through rendezvous point(s)), a distributed or a centralized administration, the mesh-first or the tree-first approach for constructing source-specific or shared trees based on some metrics. Such characteristics of the group management mechanism are primarily driven by the application domain. For instance, single-source video streaming with large number of receivers usually involves a distributed group management and construction of a source-specific tree based on bandwidth and delay metrics, whereas medium-sized conferencing applications may involve the mesh-first construction of a shared tree based on bandwidth and delay and can afford a centralized approach to the group management. These characteristics are described next.

Mesh First versus Tree First

There are two basic approaches to configure the data distribution pathways: mesh-first, and tree-first. In the mesh-first approach, members keep a connected mesh topology (Figure 6(a)) among themselves. Usually the source is chosen as a root and a routing algorithm is run over the mesh relative to the root to build the tree. This mesh topology is explicitly created at the beginning, hence it is known. On the other hand, the resulting tree topology is unknown. So the quality of the tree depends on the quality of the mesh chosen. By contrast, in the tree-first approach, the tree is built directly without any mesh. The members explicitly select their parent from the known members in the tree. This may require running an algorithm to detect and avoid loops, and to ensure that the structure is indeed a tree. There is no intervening mesh topology here. The reason for using the tree-first approach over the mesh-first approach is that the tree-first approach gives direct control over the tree. This control is valuable for different aspects such as maintaining strict control over the fan-out, selecting a best parent neighbor that has enough resources, or responding to the failed members with a minimum impact to the tree. Another advantage of the tree first approach is independent actions from each member. It makes the protocol simple as it has a lower communication overhead. But when a member changes a parent, it drags all of its descendents with it (Figure 6(c)). This is desirable in the sense that the descendents do not need to change their neighbors; in fact, they are indeed unaware of the incident. However, this can also result in lopsided trees, which are “uneven: and less efficient than correctly formed trees. The advantage of the mesh-first approach becomes apparent here as it gives more freedom to refine the tree. It is possible to manipulate the tree topology to a significant extent by selecting mesh neighbors and changing the metrics. A mesh-first approach is therefore more robust and responsive to tree partitions and is more suitable for multi-source applications, at the cost of higher control overhead.

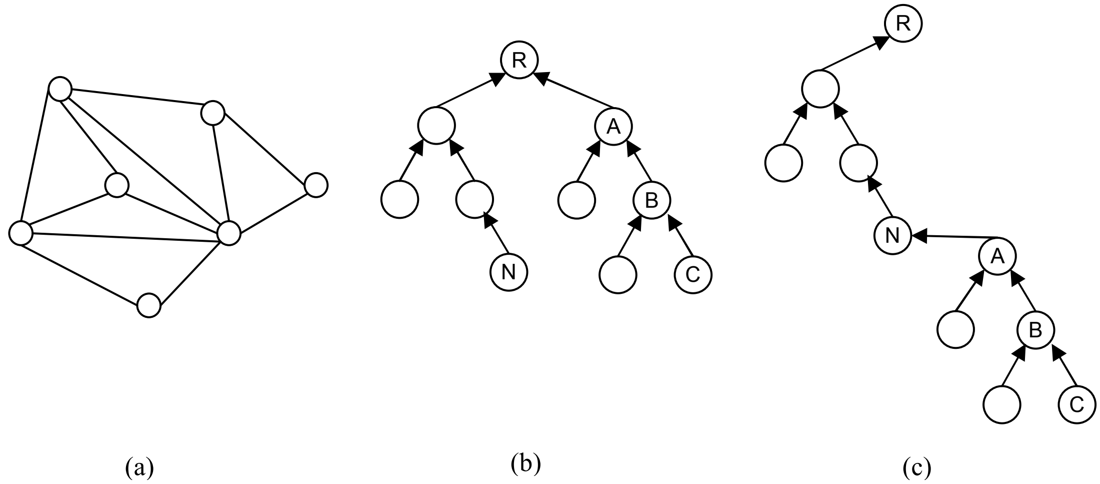


Figure 6. (a) A mesh: a network topology with many redundant interconnections between network nodes (b) Initial tree (c) Lopsided Tree

Source Specific Tree versus Shared Tree

In multicasting two conflicting design goals are (a) minimizing the length of the path (usually in terms hops/end-to-end delay) to a specific individual destination and (b) minimizing the total number of hops or the cumulative end-to-end delay to forward the packet to all the destinations. To the best of our knowledge, there is yet no good heuristic to balance these two conflicting goals. The choice between a source-specific tree (case a) and shared tree (case b) usually depends on whether the multiple sources use the same overlay for data distribution or not. Shared trees are preferred when there is a multiparty communication; i.e. multiple sources such as online games. It is better than source specific tree in terms of the maintenance cost. Source specific tree, on the other hand, allows for optimization of the tree for a given source, but cannot support efficiently multiple sources on that tree.

Distributed versus Centralized

Although intuitively one might think that a distributed routing approach better fits large-scale applications to efficiently manage group communication, there are still incentives for a centralized approach [35]. In a distributed approach, the workload of maintaining the tree is evenly distributed among the root nodes. But the synchronous communication among the members for real-time applications like media streaming is hard to ensure due to the inherent decision-making delay in distributed techniques. The centralized management of multicast groups is a fair choice for small-scale applications. It is simple and easy to deploy. Naturally there is always a risk of single point of failure in centralized system. Designers must balance simplicity and practicality versus robustness when choosing one of these approaches in designing an ALM protocol.

IP Multicast Compatibility

It would be beneficial if an ALM protocol exploits IP multicasting where it is available. This is advantageous for applications where the existing infrastructure of IP Multicasting (typically in a large organization or company) can be further enhanced to support Internet users. An example is the Hybrid Distributed Simulation Protocol (HDSP), which allows military simulations, traditionally performed on expensive networking infrastructure, to be extended to home users and/or between multiple multicast sites [84]. Another example is Island Multicast (IM), which integrates IP multicast with ALM [80]. It has a two level architecture, with the top level concerned with packet delivery between "islands" using unicast mechanism and the bottom level concerned with packet delivery among the members in an island using IP multicast.

Refinement

Depending upon the order of joining requests for the same set of nodes, constructed trees might be different and have different perception quality. The quality of an ALM path between any pair of members is comparable to the quality of the unicast path between that pair of members. This implies requirement of a minimum diameter tree. But, as the protocol constructs the tree in real time and has no a-priori knowledge of node arrivals it is hard to construct this optimum tree. Refinement is a solution to this problem. It moves the overlay structure from the local optimum to the global optimum and improves the system's performance. But excessive refinement makes the structure unstable due to the ad hoc natures of node behaviour. Moreover, the effectiveness of the refinement to real-time applications is questionable due to interrupted data distributions among the members. A designer must thus carefully choose the depth and frequency of tree refinement for a given application.

D. Routing Mechanism

Once the overall group management has been designed and the various choices are decided on, the most important part of the design is how the tree (or a different structure) is formed that provides the multicast service. This greatly depends on the previous choices such as application domain (mainly determining the quality metric and constraints), the deployment level (mainly determining the resources available to each node in terms of permanency as well as bandwidth) and group management. Design of the routing mechanism typically involves a (heuristic) solution to a graph theory problem. That is, given a certain graph (i.e. a certain existing structure of nodes) and certain constraints on each node (e.g. inbound and outbound bandwidth constraints), the problem involves the construction of a structure connecting the group of users (or in case of a tree, connecting a source to all its recipients) that satisfies a given requirement; e.g. minimum overlay delay or minimum worst case delay. The solution to the problem largely comprises the routing mechanisms; the routing mechanism must then be augmented with stipulations about nodes leaving the multicast structure, as well as possibly periodic or event-based refinement strategies for the improvement of the structure. In this section we provide a survey of common approaches to the routing mechanism:

1. Group 1: Shortest Path

The aim of this group is to construct degree constraint minimum diameter spanning tree. Here they use RTT measurement to determine the shortest path tree from the source to the end hosts and minimize the time delay for each application while considering the degree constraint and QoS. A Shortest Path Tree (SPT) constructs a minimum cost path from a source node to all its receivers (see chapter 25 of [53] for Dijkstra's algorithm for building SPTs). An SPT or one of its variants is commonly used by ALM protocols (such as Yoid [19], SpreadIt [13], TAG [28], RITA [46]) in order to construct a source-specific multicast tree or in graph theoretic terms a rooted tree. Figure 7(b) shows the SPT rooted at the filled-in node. It is important to note that both MST and SPT can be modified to respect degree constraints of each node [54][43].

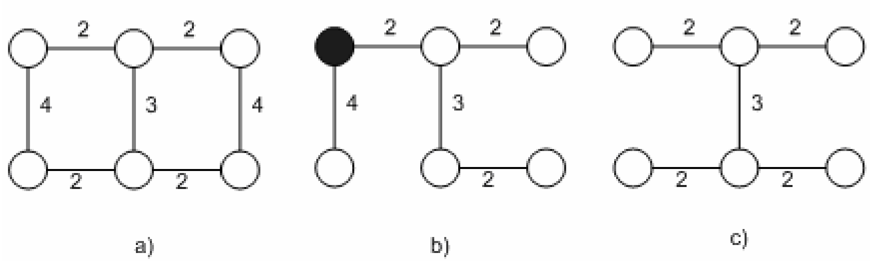


Figure 7. a) A graph with link costs b) Shortest Path Tree b) Minimum Spanning Tree

2. Group 2: Minimum Spanning Tree

This group does not worry about degree constraint of nodes and just tries to construct a 'low cost' tree or in other words a Minimum Spanning Tree. Given a graph with a cost associated with each edge (usually delay), a Minimum Spanning Tree (MST) is a tree with minimum total cost spanning all the members (see Chapter 24 of [53] for Kruskal and Prim's algorithms for building MSTs). Given the graph with edge costs shown in Figure 7(a), an MST is constructed to have the minimum total cost as shown in Figure 7(c) (total cost is 11 in this example). A MST is commonly used by a centralized ALM protocol such as ALMI [36] and HBM [40] in order to construct a low cost shared tree that is not rooted at any particular source (a shared tree implies that all nodes use the same tree to distribute their data).

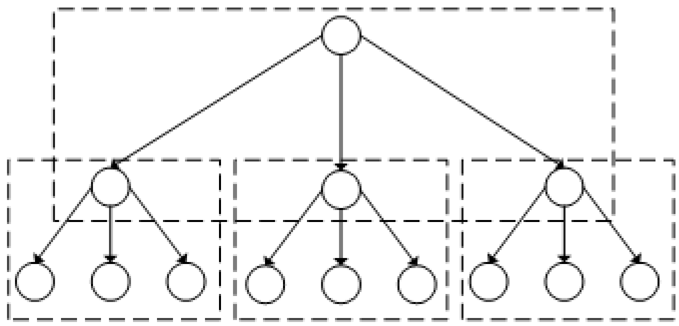


Figure 8. A hierarchical cluster of nodes with cluster size 4

3. Group 3: Clustering Structure

This group constructs a cluster of nodes that can be used to construct trees. In order to better organize the overlay tree and reduce control message overhead, some ALM protocols such as ZIGZAG [44] and NICE [3] construct a hierarchical cluster of nodes with each cluster having a 'head' representing it in the higher layer (Figure 8). The advantage of a hierarchical clustering approach to multicast tree routing is the reduction in control overhead (nodes keep states only about a subset of other nodes) and faster joining and management of the tree at the cost of a sub-optimal tree and a lack of hard guarantees on the degree limitation of each node.

4. Group 4: Peer-to-Peer Structure

In P2P structure, the routing is simply done through reverse-path forwarding or forward-path forwarding or in some cases a combination of both types. From Table 2, we observe that many ALM protocols (such as RMX [9], Gossamer [7], Bayeux [52], Borg [49], Scribe [6]) operate based on an existing peer-to-peer substrate that serves as a mesh on top of which an overlay multicast tree can be constructed using either a reverse-path forwarding scheme (Gossamer [7], RMX [9], Scribe [6]), a forward-path forwarding scheme (Bayeux [52]) or both (Borg [49]). The advantage of these approaches includes low control overhead and distributed management of the multicast tree but they do not restrict the degree of each node and are sub-optimal.

It should be noted that Peer to Peer technology is a research area of its own, and a big one at that. In general, a P2P system is a system where peers communicate directly with one another. As such, there is not necessarily a multicasting component, and therefore outside the scope of this paper. For example, Skype [86] is a well-known P2P Internet telephony system that does not use multicasting. The P2P aspect mentioned here applies only to ALM systems that happen to also have a P2P component, such as TVUPlayer [87], Sopcast [88], and PPLive [89], to name a few.

E. Degree-constraint routing

The feasibility of carrying multicast data over the ALM depends on whether or not there is available bandwidth (out degree) at the end hosts. Usually end hosts have asymmetric downloading and uploading speeds. Moreover, heterogeneity of outgoing bandwidth of end hosts forces protocols to consider realistic degree assignment. It may happen that a user has zero out degree, i.e. pure receiver. In the real world, around 50% of hosts have zero out degree to support streaming bit rate [71]. From a practical perspective, the asymmetric bandwidth fact cannot be ignored and should be taken into consideration to assign out degrees to nodes during implementation. It reflects the maximum bandwidth a node can provide. For example, if a node has an out degree of 4, it means it can support at most 4 children. There are two types of degree constrains. In some cases there is only a bound for the maximum number of edges that a node can have that is usually flexible and can be changed according to different applications. In other cases there is a fixed bound that is restrict and predetermined. Minimum Spanning Tree (MST) and Shortest Path Tree (SPT) routing algorithms can be modified to respect the degree constraints of each node. The problem of finding minimum-cost degree-constrained multicast trees or degree-constrained Steiner trees is NP-complete [72]. There exists several heuristic approximation algorithms addressing this problem [53][74][75][76][77]. Some of these algorithms (such as [75][76]) do not provide exact guarantees on the degree of each node in the tree and instead provide a bound on the worst-case degree. Others focus on constructing a single tree and do not consider multiple trees over the same graph ([53][77][78]). Though there has been some research with regards to constructing multiple trees on a shared graph [79], they still only provide a bound on the worst case (maximum) degree of any node as opposed to guarantees on the individual maximum degree for every node as is required for a protocol supporting multi-source collaboration applications.

IV. SURVEY AND CLASSIFICATION OF ALM PROTOCOLS

As mentioned previously, a plethora of ALM protocols has emerged from both the research and practice arenas. This section lists a number of such protocols that were published between 1995 and 2005. To simply list these protocols would not serve much purpose to the reader. As such, we have tabulated the surveyed protocols based on their “class”, in order to provide practitioners in the field with a comparative perceptive of these protocols. We have used the design, routing, application, and group characteristics described in section III in order to create a classification of the protocols. The ALM protocol are categorized here based on their routing characteristics described in Section III D and E (Table 2), and application/group configurations as described in Section III A, B, and C (Table 3).

Table 2. Classification of ALM protocols based on routing algorithm

ALM Protocol	Routing Group	Degree constraint	Tree refinement	New node joins at	Control Overhead	Features
ALMI [36]	2	No	Periodically	Closest node	O(N)	Minimizes average cost of shortest path trees rooted at group members
Amcast [43]	2	Restricted	No	Not specified	O(log N)	Minimize diameter while Respecting the degree constraints
Bayeux [52]	4	Bounded	Yes	Closest node	O(log N)	- Forwarding path - Tapestry structure
Borg [49]	4	Bounded	Yes	Closest node	O($\log_2^b N$)	- Both forwarding path and reverse path - Pastry structure
BTP* [55]	1,2	Bounded	Depending on application	Not specified	Total number of switches	Minimizes root-path latency for a specific node
CAN Multicast [39]	4	Bounded	No	Closest node	O(d)	CAN structure
CoopNet [35]	1	Bounded	No	Closest node	O(log N)	Minimizes the average delay

ALM Protocol	Routing Group	Degree constraint	Tree refinement	New node joins at	Control Overhead	Features
Delaunay [30]	4	Bounded	No	Not applicable	-	Mesh structure
Gossamer and Scattercast [7]	3	Restricted	Yes	Head of the island	-	- Simple clustering - Based on Scattercast -RMXs organize themselves into a spanning tree - A hierarchy of traffic classes for bandwidth allocation
HBM [40]	2	No	Periodically	Closest node	O(log N)	Minimizes the average delay
HMTP [48]	3	No	Periodically	DM of the island	-	-Simple clustering -uses DVMRP for spanning tree -Minimum average delay
MVEMP [57]	1	Yes	No	Closest to root	$O(n^2)$	Multiple degree/bandwidth constraint trees minimizing delay
Narada [10]	1	Bounded	Periodically	Random join	$O(N^2)$	
NICE [3]	3	Restricted	Periodically	Cluster head	O(log N)	-Hierarchical clustering -Minimizes maximum distance to all other hosts in the cluster
OMNI [4]	1	Restricted	Periodically	Source	O(log N)	-Minimizes the average delay - considers Minimum maximum latency
OveRCast [26]	1	No	Periodically	Source	O(log N)	Minimize the average bandwidth
ProBaSS [58]	1	Yes	No	Closest node	-	Proxy-based single-source ALM protocol
PST* [56]	1,2	Yes	Yes	Not specified	Total number of switches	Incorporate application-specified priority for the packet
RITA [46]	1	Restricted	When application quality is violated	Closest node	O(log N)	Minimizes average delay

ALM Protocol	Routing Group	Degree constraint	Tree refinement	New node joins at	Control Overhead	Features
RMX [9]	3	Bounded	Yes	Cluster head	-	-Simple clustering -Based on Scattercast -RMXs organize themselves into a spanning tree - A hierarchy of traffic classes for bandwidth allocation.
Scribe [6]	4	Bounded	Yes	Closest node	$O(\log_2^b N)$	- Reverse path - Pastry
SpreadIt [13]	1	Restricted	No	Source	$O(d^L)$	Minimizes the average delay
TAG [28]	1	Bounded	No	Source	O(k(log N))	Minimizes the average delay
TBCP [31]	2	Yes	No	Root	-	end-system multicast with dynamic group join and leave
Yoid [19]	1	Restricted	Periodically	Closest node	O(log N)	Minimizes the average delay
ZIGZAG [44]	3	Restricted	Periodically	Cluster head	O (K*log N) or O (k)	-Hierarchical clustering -Minimum average delay

*BTP and PST belong to both group one and two since they use SPF when minimizing delay and MST when lower cost is desired

Table 3. Classification of ALM protocols based on application/group configuration

ALM Protocol	Application Domain	Deployment Level	Peer-to-peer substrate required	Exploit IP Multicast	Centralized or distributed	Shared or source-specific tree	Metric	Tree-first or Mesh-first	Refinement
ALMI [36]	2	End-system	-	No	C	Shared	Delay	Tree-first	Yes
Amcast [43]	1	Proxy-based		No	C	Shared	Delay Bandwidth	Tree-first	No
Bayeux [52]	1	Proxy-based	CAN	Yes	D	Source-specific	Delay	Mesh-first	Yes
Borg [49]	3	Proxy-based	Tapestry	No	D	Source-specific	Delay Bandwidth	Mesh-first	No
BTP [55]	4	End system	-	No	D	Both	Delay	Tree-first	No

ALM Protocol	Application Domain	Deployment Level	Peer-to-peer substrate required	Exploit IP Multicast	Centralized or distributed	Shared or source-specific tree	Metric	Tree-first or Mesh-first	Refinement
CAN Multicast [39]	3	Proxy-based	Pastry	No	D	Source-specific	Delay	Mesh*	No
CoopNet [35]	1	End-system	-	No	C	Source-specific	Delay Bandwidth	Tree-first	No
Delaunay [30]	3	Proxy-based	-	No	D	Source-specific	Geographical position	Mesh$	No
Gossamer [7]	3	Proxy-based	-	Yes	D	Source-specific	Delay Bandwidth	Mesh-first	Yes
HBM [40]	2	Combined	Pastry	No	C	Shared	Delay	Tree-first	Yes
HMTP [48]	1	Proxy-based	-	Yes	D	Shared	Delay	Tree-first	Yes
MVEMP [57]	2	End system	No	No	C	Source specific	Bandwidth, delay	Mesh-first	No
Narada [10]	2	End-system	-	No	D	Source-specific	Delay Bandwidth	Mesh-first	Yes
NICE [3]	1	End-system	-	No	D	Source-specific	Delay Bandwidth	Mesh- first~	Yes
OMNI [4]	1	Proxy-based	-	Yes	D	Source-specific	Delay Bandwidth	Tree-first	Yes
OverCast [26]	4	Proxy-based	-	No	D	Source-specific	Bandwidth	Tree-first	No
ProBaSS [58]	1	Proxy-based	Yes	No	C	Source-specific	Delay	Tree-first	No
PST [56]	2	End system	No	No	D	Source Specific	Priority, Delay	Tree-first	Yes
RITA [46]	1	Proxy-based	-	No	D	Source-specific	Delay Bandwidth	Mesh-first	Yes
RMX [9]	4	Proxy-based	ScatterCast	Yes	D	Shared	Delay Bandwidth	Mesh-first	Yes

ALM Protocol	Application Domain	Deployment Level	Peer-to-peer substrate required	Exploit IP Multicast	Centralized or distributed	Shared or source-specific tree	Metric	Tree-first or Mesh-first	Refinement
Scribe [6]	3	Proxy-based	ScatterCast	No	D	Source-specific	Delay Bandwidth&	Mesh-first	Yes
SpreadIt [13]	1	End-system	-	No	D	Source-specific	Bandwidth Delay	Tree-first	No
TAG [28]	1	End-system	-	No	D	Source-specific	Topology Bandwidth	Tree-first	No
TBCP [31]	3	End-system	-	No	D	Source-specific	Delay Bandwidth	Tree-first	No
Yoid [19]	3	End-system	-	Yes	D	Shared	Bandwidth Delay	Tree-first!	Yes
ZIGZAG [44]	1	End-system	-	No	D	Source-specific	Delay Bandwidth	Mesh-first~	Yes

* CAN-Multicast doesn't make a tree (duplicate copies)
$ Using Delaunay triangulation, an explicit tree constructing algorithm is not actually needed
~ A hierarchical cluster of nodes is constructed and a tree is built on top of this hierarchy
& since the out degree of a node is potentially unbounded, they see if a node is overwhelmed and try to offload
! A mesh also exists but is constructed after the tree

V. A CLOSER LOOK

While covering the details of each of the ALM protocols mentioned in the above tables will not fit in one paper, it is beneficial to look at some of them in order to get a better understanding of the inner working principles of an ALM protocol. This can also serve as a tutorial for those interested in developing their own ALM protocol for a specific application. For this purpose, we have chosen to look into three of the more popular protocols: ZIGZAG **[44]**, NICE **[3]**, and OMNI **[4]**.

A. ZIGZAG

ZIGZAG [44] is a single source, degree-bounded application layer multicasting approach for media streaming. It organizes receivers into a hierarchy of clusters and builds the multicast tree on top of it. The recursive rules of organizing the nodes into a multi-layer hierarchy of clusters are demonstrated in Figure 9. Assume that, H is the number of layers and $K > 3$ is a constant. Layer 0 contains all of the nodes. Nodes in layer $j < H-1$ are partitioned into clusters of sizes in $[k, 3k]$, where layer $H - 1$ has only one cluster of size $[2, 3k]$. A node in a cluster at layer $j < H$ is selected to be the *head* of that cluster. This head becomes a member of layer $j + 1$ if $j < H - 1$. The server S is by default the head of any cluster where it belongs.

The administrative organization represents logical relationships while the physical relationships among the nodes are maintained through a multicast tree (Figure 10). The rules to define the multicast tree in ZIGZAG are as follows: A node may not have any link to or from any other node except at the highest layer (node 4 at layer 1, Figure 10). At the highest layer, a node can only have links to its foreign subordinates (node 4 at layer 2 only links to nodes 5, 6, and 7 at layer 1, which are foreign subordinates of

4, and the only exception is the server; at the highest layer, Figure 10). At layer $j < H-1$, non-head members of a cluster cannot get the content from their head, instead they get the content directly from a foreign head (non-head nodes in layer-0 cluster of node 1 have a link from their foreign head 2; nodes 1, 2 and 3 have a link from their foreign head S, Figure 10).

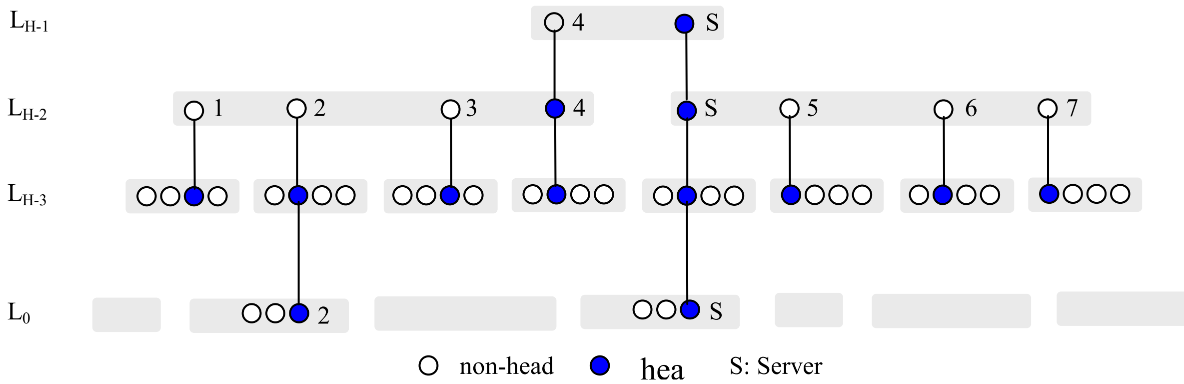


Figure 9. Administrative organization of nodes [44]

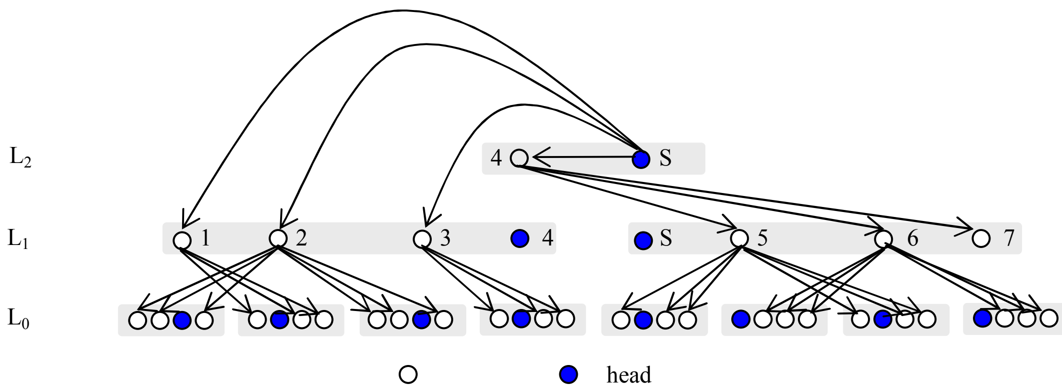


Figure 10. The multicast tree of nodes ($H = 3, K = 4$) [44]

The motivation for not using the head as the parent for its subordinates in ZIGZAG is justified as follows. The members of a cluster receive content from their cluster head. If the highest layer of node X is j, X would have links to its subordinates at each layer $j-1, j-2, \ldots, 0$ where it belongs to. Since j can be H - 1, the worst-case node degree would be $H \times (3k - 1) = \Omega(\log_k N)$. Thus nodes closer to the source have large out-degrees and run out their bandwidth quickly, which might not be acceptable for bandwidth-intensive media streaming applications. Moreover when the parent node fails, the head of its children is still working and helps to reconnect the children to the new parent immediately. It is proven that the worst case degree of a node and the height of the multicast tree are $O(k^2)$ and $O(\log_k N)$ respectively [44]. The join request is propagated down the multicast tree until a suitable parent is found while keeping the structure defined by the rules. It finds a node that it is closest to the lowest layer. ZIGZAG periodically runs optimization algorithms to improve the quality of service to clients. Degree-based and capacity-based switching approaches are taken to balance the degree and the load of the nodes respectively.

B. NICE

NICE [3] is a recursive acronym which stands for the NICE Internet Cooperative Environment. This scalable application layer multicast protocol uses a hierarchical clustering approach to support a larger number of receivers. NICE was designed to provide architecture for low bandwidth soft real-time data stream applications such as real-time stock quotes and updates and Internet radio.

It organizes hosts in a hierarchy of layers and each layer has several clusters of hosts. The lowest layer in the hierarchy is denoted by L_0. The size of the cluster is between K to $3K - 1$, where K is a constant. Each cluster has a leader to communicate with higher layers. It is chosen at the center of the cluster; i.e., the leader has the minimum maximum distance to all other hosts in the cluster. Hierarchical arrangement of hosts in NICE is presented in Figure 11.

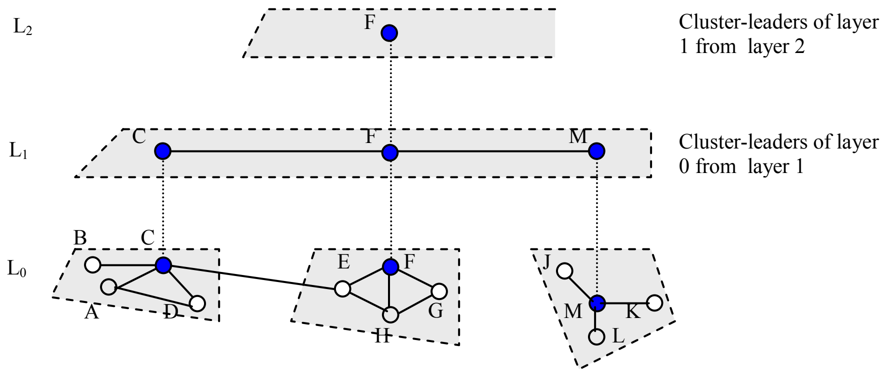


Figure 11. Hierarchical arrangement of hosts in NICE [3]

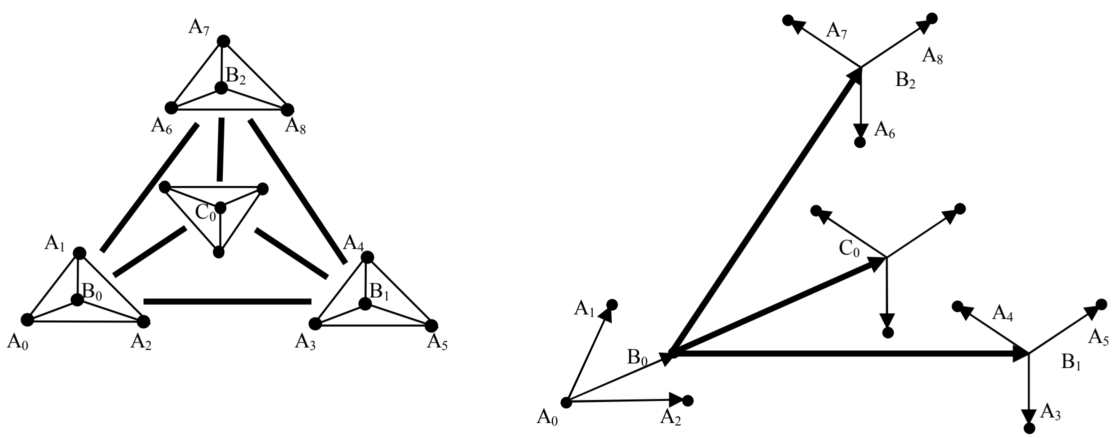


Figure 12. Control and data delivery paths for a two layer hierarchy in NICE [3]

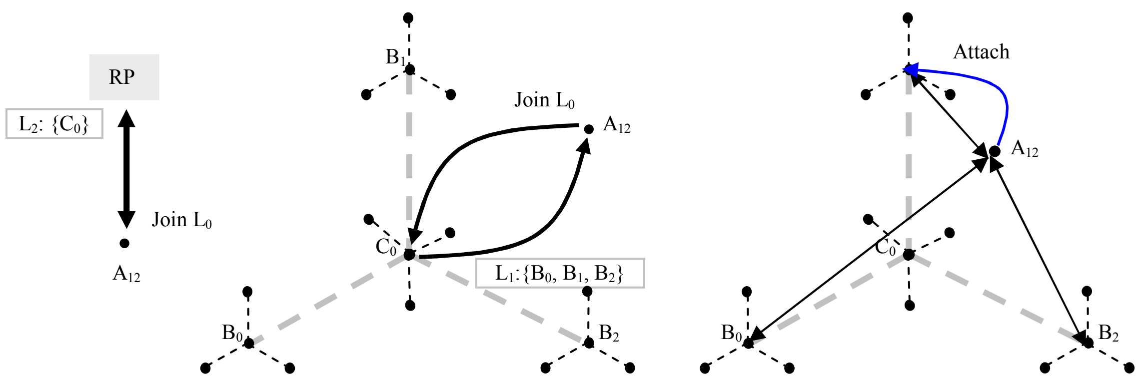


Figure 13. Joining process in NICE [3]

This hierarchical structure ensures following properties for the distribution of hosts in different layers,

- A host only belongs to a single cluster at any layer
- A host is a member of all layers $L_0, L_1, \ldots L_{j-1}$, in fact a leader, if it stays in layer L_j
- A host is in layer L_j if it is a leader L_{j-1}

- Cluster size is bounded between K and $3K-1$ except the highest layer that has only a single member.
- There are at most $\log_k N$ layers.

On top of the hierarchy, NICE can build source-specific trees of different kind. Figure 12 is an example of control and data delivery paths for a two layer hierarchy. All A_i hosts are in layer L_0 and distributed in different clusters at that layer. All B_0 hosts are members of both layers, namely L_0 and L_1. The layer L_1 has only one cluster consisting of all the B_i hosts and C_o, where it is the leader at this cluster and layer. For example, member A_0 only belongs to layer L_0 and thus has control paths to A_1, A_2 and B_0 whereas member B_0 stays in both layers L_0 and L_1 and therefore its control paths extends to both member of L_0 cluster (i.e. A_0, A_1, A_2) and L_1 cluster (i.e. B_1, B_2, C_0). NICE assumes that there is a special node named Rendezvous Point (RP) which is known to all members. Figure 13 is an example of the join procedure. Let us assume that host A_{12} wants to join the multicast group. It sends a join query to the RP. The RP responds with a list of hosts that are present at the highest layer in the hierarchy. The joining host then figures out the best one in the highest layer based on distance. In the example, the highest layer L_2 has just one member, namely C_0. Host C_0 then informs A_{12} about the three other members (B_0, B_1 and B_2) in its L_1 cluster. A_{12} then contacts each of the members to identify the closest member among them. This iterative procedure continues until it reaches to L_0 cluster.

NICE allows nodes in a cluster to exchange periodic messages to maintain appropriate peer relationships. Cluster leader also exchanges messages to its higher layer members. Cluster leader is responsible of maintaining proper cluster size and thus applies the splitting or the merging algorithm when needed. Since node joining and leaving may result in changes, the cluster leader has methods for refinement. Therefore, each member, H, in any layer L_i periodically probes all members in its super-cluster - the leaders of layer L_i clusters - to identify the closest member to itself in the super-cluster. If there is any improvement, it leaves the current cluster and switches to the new cluster. This refinement approach detects inaccurate placement of hosts in clusters and gradually moves to global optimal hierarchy.

C. OMNI

The Overlay Multicast Network Infrastructure (OMNI) [4] offers overlay architecture to efficiently implement media streaming applications. Service providers deploy Multicast Service Nodes (MSNs) that act as application layer multicast forwarding entities for a set of clients. Most importantly, MSNs run a distributed protocol to form a multicast data delivery backbone. The data delivery path can be built using network layer multicast, application layer multicast, or a sequence of unicasts that is independent of data delivery path used in the overlay backbone. OMNI's architecture is shown in Figure 14.

The goal of OMNI is to improve, i.e. minimize, the latencies to the entire client set. MSNs are given priorities based on the population of clients. Thus relative importance of the MSNs varies as clients join and leave the session. OMNI formulates its objective to construct the minimum average-latency degree-bounded spanning tree with different importance to MSNs and proposes iterative distributed solution. The multicast overlay network can be modeled as a complete directed graph, defined by $G = (V, E)$, where V is the set of vertices and $E = V \times V$ is the set of edges. Each vertex in V corresponds to an MSN. The $edge(i, j)$ in G represents the unicast path from MSN i to MSN j. The overlay latency $L_{i,j}$, from MSN i to MSN j, is the summation of all the unicast latencies along the overlay path from i to j on the tree T. On the other hand, Client i has a latency consisting of (a) the latency from the media source to the root MSN r, (b) the overlay latency $L_{r,d}$ on the OMNI path from root MSN r to destination MSN d and (c) the latency from the MSN d to the client i. The arrangement of the MSNs affects only the overlay latency, and the other two components do not depend upon the OMNI overlay structure. Hence, OMNI only tries to optimize the overlay latency $L_{r,d}$ between the root MSN and the destination MSN d in constructing the OMNI overlay backbone. OMNI solves the Minimum average-latency degree-bounded directed spanning tree problem as follows: *Find a directed spanning tree, T of G rooted at the MSN, r, satisfying the degree-constraint at each node, such that* $\sum_{i \in M} c_i L_{r,i}$ *is minimized where M is the set of all MSN and* c_i *is the number of clients served by the MSN i.*

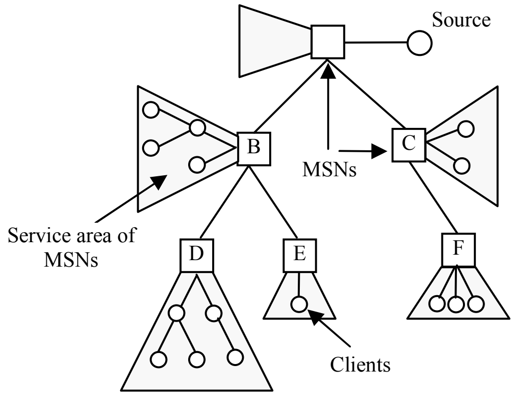


Figure 14. OMNI architecture [4]

OMNI also defines two terms: *aggregate subtree clients (S_i)* and *aggregate subtree latency (Λ_i)*. The first one denotes the entire set of clients served by all MSNs in the subtree rooted at MSN *i*, while the aggregate subtree latency denotes the summation of overlay latency of each MSN in the subtree, from MSN *i*, which is weighted by the number of clients at that MSN. Mathematically, we can say that:

$$s_i = c_i + \sum_{j \in Childrean(i)} s_j$$

$$\Lambda_i = \begin{cases} 0 & \text{if i is leaf MSN} \\ \sum_{j \in Children(i)} s_j l_{i,j} + \Lambda j & \text{otherwise} \end{cases}$$

Here, *Children(i)* is the set of children of *i* in the overlay tree and c_i denotes the number of clients directly served by *i*. Each MSN *i* keeps the following state information: (a) the overlay path from the root to itself, (b) the aggregate subtree clients, s_i, (c) the aggregate subtree latency, Λ_i, and (d) the unicast latency between itself and tree neighbors. OMNI initially runs as an initialization algorithm and then incrementally refines the overlay tree. Each MSN sends a join request to the root MSN after measuring the unicast latency between itself and the root MSN. A join request is simply a tuple like <*Latency to root, Degree bound*>. During the initialization phase, MSNs have no information about the clients' population. The root MSN creates the initial data delivery tree using a centralized algorithm by exploiting the stored join request information. It then distributes the data delivery structure to the MSNs. Due to changes in network condition and clients' distribution to MSNs, OMNI continuously applies refinement operations to discover a better data delivery tree. It defines five local refinement operations, namely child promote, parent child swap, iso level-2 swap, iso level-2 transfer, aniso level-1-2 swap. The aggregate subtree latency on the tree for the min max latency problem is reduced by local refinement operations. These operations guide the objective function to the local optimum but they alone cannot guarantee global optimal. Therefore OMNI defines a probabilistic transformation and random swap procedure to allow MSNs to discover global optimal.

VI. OPEN ISSUES AND FUTURE WORK

The list of ALM protocols presented in this article covers the diversity of approaches to ALM protocols and serves to illustrate their characteristics, but it is not an exhaustive list since it focuses on relatively earlier efforts at the exclusion of the protocols that have currently emerged. More recent endeavors examine the issue of trust in overlay networks [29], handling heterogeneity of users [45], providing resilience [2], and taking into account node availability [20] as well as high-bandwidth file transfer and downloading [5]. BP (Branching point) based approaches have many invaluable features like incremental deployment, low memory requirement and high scalability. BMP [59] (Branching based Multicast Protocol) is a BP protocol. BMP's packet forwarding method has very little impact on unicast packet forwarding. It avoids packet duplications, in other BP based approaches which occurs in the presence of network asymmetry. Join process has some level of locality property and many join process can be done simultaneously. [60] shows how to directly map the node load to the delay penalty at the application host, and create a new model that captures the trade offs between the desire to select shortest path trees and the need to constrain the load on the hosts. VRing [61] (Virtual Ring), an application layer multicast protocol, establishes a virtual ring as an overlay network among the multicast group members in a self-organizing and distributed manner. It has a higher path stretch and a higher link stress than some other ALM protocols. But it provides less control overhead, consumes less bandwidth, and provides lower average degree node. The major problem of a ring based topology is the potentially large routing delay a packet may incur especially for large multicast group. [62] constructs topologically-aware data paths which are based on topological clustering of multicast group members. It does not require any exact network topology information, but instead requires the relative location information of members using landmarks. Protocol partitions the members into topologically-aware clusters based on the ordering of their close landmarks. Topologically-aware data paths can reduce unnecessary high latency and redundant network resource usage with low overhead over existing scalable approaches. SOT (Secure Overlay Tree) offers data confidentiality in ALM [63]. To achieve data confidentiality, data encryption keys are shared among the multicast group members. For a large and dynamic group, re-encryption and re-keying operations incur high processing operation at nodes. SOT introduces a scalable scheme which clusters ALM peers so as to localize re-keying within a cluster and to limit re-encryption at cluster boundaries, thereby minimizing the total nodal processing overhead with little cost in network performance in terms of network stress and delay. A new algorithm, called Fastcast [64], is introduced. It is a root based, online, and topology-aware ALM, Fastcast is controlled by a parameter, and by changing this parameter it is possible to control the tradeoff between used traffic and the worst-case length of the application layer path. ALM algorithms for P2P applications can benefit form the possibility of limiting the number of children in the ALM tree, since many nodes could be connected by slow modem connections.

An open issue for all ALM protocol is that of tree refinement: the reorganization or shuffling of the nodes in the tree. This is usually conducted to enhance the system performance. In ALM, the quality of the path between any pair of members is comparable to the quality of the unicast path between that pair of members. Typically a lower diameter tree performs better than a higher diameter tree. Hence, refinement is a way to improve the quality of the ALM structure once it is already constructed. A key point is that, if a node with zero out-degree joins to a multicast session, the tree can not be extended beyond that point which ultimately increases the height of the tree. To handle such situations refinement acts as a solution. But it is an expensive operation and thus should be applied in special conditions. This is because protocols require too much information to carry out the operation. Research should therefore be conducted to find efficient mechanisms to determine whether or not refinement is applicable to a particular node. If so, how much it improves the performance of the system, say in terms average latency or other parameters. The protocol should also be aware of the transient period of the refinement when it actually takes place – does it affects its dependent nodes, if so by how much. Furthermore, the protocol must consider its side effects like churn that may lead to inconsistent systems. As an example, OMNI uses local transformations (child promote, parent-child swap, iso-level-2 transfer, aniso+level-1-2 swap) and probabilistic transformations (simulated annealing) to refine its structure. As it is an expensive operation and requires extra care, frequent refinement may adversely affects the system performance. Most of the ALM protocols strategically and infrequently apply refinement operation.

Another open issue is balancing the two conflicting design goals mentioned in Section III: (a) minimizing the length of the paths (usually in terms hops) to the individual destinations and (b) minimizing the total number of hops to forward the packet to all the destinations. The minimum spanning tree (MST) and the shortest path tree (SPT) are two well-known data distribution methods in ALM. The MST optimizes the resource usage of the multicast tree but the pair-wise paths may not be optimal and can cause large end-to-end delays. Hence it is suitable for non-interactive data dissemination when end-to-end delays are not an issue. In SPT, the distribution tree will consist of separate unicast connections from the sender to each receiver. It is optimal from the source to the receiver in terms of end-to-end delay but it causes high consumption of network resources. Moreover, it is not practical when the sender's bandwidth is not sufficient to serve all receivers simultaneously. Scaleable ALM systems usually require clustering of the nodes. The advantage of a hierarchical clustering is the reduction in control overhead as nodes keep states only about a subset of other nodes. Furthermore, faster joining and group management is possible at the cost of a sub-optimal tree.

VII. CONCLUSION

In this article, we looked at the roots and rationale behind Application Layer Multicasting. Compared to IP multicasting, ALM has certain disadvantages such as longer delays and less efficient traffic generation. However, due to its overwhelming advantages for certain applications, such as immediate deploy-ability and application-specific adaptation, it can be a practical solution to many of the existing problems in multi-user communications. The fact that an ALM protocol can be developed and deployed on the Internet without the need to make any changes to the existing network infrastructure, and the ability to evolve and apply modifications to the protocol quickly and easily at the application layer has helped the ALM approach to have a quicker start compared to other multi-user communications solutions. These advantages have caused the serious consideration and development of ALM protocols which in turn would lead to the creation of new applications and communications paradigms on the Internet.

The popularity of application layer multicasting continues to grow in different fields as an alternative to native IP multicasting. These include news groups, video conferencing, internet games, internet jukebox, interactive chat-lines, distant learning, and video on demand just to name a few. Although ALM is considered as an active research topic over the last decade, still there are many open issues to continue research for creating efficient and robust ALM protocols in terms of application domain requirements and the quality of service. This survey paper functions as a reference guide for new researchers in this field to use as a starting point.

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