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IP multicast resource and topology discovery using a fan-out decrement mechanism ☆

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Abstract

As the use of IP multicast sessions becomes widespread, the potential benefits derived from currently unavailable topological information on multicast distribution trees may become increasingly critical. In this paper we propose a framework for discovering the topology of *shared* multicast trees based on a novel *fan-out decrement* mechanism analogous to time-to-live (TTL) decrementing in IP. We propose an algorithm for topology discovery based on the matrix of path/fan-out distances among a set of E session members—the algorithm's computational complexity is $O(|E|^2)$. We exhibit sufficient conditions for topology discovery based on a *reduced* distance matrix, and propose a practical protocol to acquire this information requiring the exchange of $2|E|$ multicast messages of size $O(|E|)$. Finally, we show how the same approach permits nodes to discover the multicast distribution tree associated with members within their fan-out/TTL scoped neighborhoods. This permits one to reduce the computational costs while making the communication costs proportional to the size of neighborhoods.

Keywords: IP multicast; Fan-out decrement; Topology discovery; Resource discovery

1. Introduction

Multicast extensions to IP [1] have enabled a wide range of applications including real-time audio and video broadcasting, shared electronic white boards, software distribution and web-casting. One of the key advantages of multicasting lies, of course, in the efficient use of network resources—a single packet traverses each link in the multicast distribution tree and is replicated at *fan-out* points. Another advantage associated with IP multicast service, is as an abstraction for group communication, that is, users can join and leave a multicast session without explicit knowledge of its membership or of the structure of the distribution tree. Despite this clean abstraction, many IP multicast services can benefit from the explicit knowledge of membership and topology information. Depending on the scope of interest, IP multicast

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resource and topology discovery problems can be classified into two categories: *global*, where one interested in discovering all the members in a multicast session and *local*, where one interested in finding a subset of members in the session and their associated topology.

From the perspective of an IP multicast service user (e.g. movie distributor, advertiser) the number of subscribers in a session, their location, and their density in a specific region may be useful information. From the perspective of a network service provider, the extent to which network resources are being used (e.g. number of links and routers) by a given multicast session may be important to assess usage costs. In both cases knowledge of the *global* multicast topology would significantly facilitate resource management. [1]

In a large scale multicast session, it is not uncommon for nearby members to cooperate and perform a common task, such as distributed computation and data sharing. In this case, the *local* topology and membership information for a neighborhood of a given node would be useful. A typical use of local resource and topology discovery is in building schemes for loss recovery and congestion control in the context of multicast sessions supporting heterogeneous receivers. While a variety of approaches have been proposed to tackle this problem, e.g. [2–6], a common thread is to recognize that performance can be enhanced by either implicitly or explicitly exploiting the structure of the multicast distribution tree. OTERS [3], Tracer [2] and GFP [7] are examples of research efforts making use of explicit topology information via MTRACE [8] and an inference technique [9] for local loss recovery. Further motivation for exposing the multicast distribution tree is given in [9,7,10].

Despite its potential usefulness, there has been surprisingly little research (see e.g. [9,11]) concerning global multicast topology discovery and even less, to our knowledge, concerning local multicast topology discovery. A large amount of work has however been devoted to Internet topology discovery (see e.g. [12–15]). By contrast with multicast topology discovery, Internet topology information can be collected during long time scales (e.g. several days or even several weeks) [12], or by passive probing [16], since the physical topology remains stable over reasonably long time periods. In the case of multicast service the character of the distribution tree is only of interest when the session is active and may change dynamically throughout that period. Thus multicast topology discovery algorithms should be able to operate online and serve as practical protocol building blocks which dynamically track membership changes. As will be discussed below, these and other requirements make proposed approaches based on end-to-end measurements [9,11], fall short as practical solutions.

The following are some desirable characteristics that a multicast topology discovery mechanism should have.

Accuracy: Topology information should be "reliable" since potentially critical decisions will be based on it.

Adaptability: A mechanism should adapt to changes in group membership or distribution path topology.

Low overheads: Computational requirements at end hosts or servers and communication overheads should be low.

Distributed: From the perspective of robustness, it is preferable that discovery be performed in a distributed manner rather than relying on central points.

With these in mind, in this paper we propose a new approach to multicast topology discovery. It is based on introducing a novel fan-out decrement mechanism to IP multicast service, which is analogous to the time-to-live (TTL), or hop count, decrement mechanism currently supported in IP. As discussed in the sequel, the proposed scheme achieves all of the desirable characteristics posed above but *only* for the case where multicast service is based on *shared tree*, e.g. core based trees (CBT) [17,18], versus source tree routing. Additionally, we propose both concepts and practical issues for *local* resource and topology discovery which enable further 'scalability' for large scale multicast applications.

[1] Throughout the paper a multicast topology refers to the multicast distribution tree constructed by multicast routing protocols.

The paper is organized as follows. Section 2 introduces the proposed fan-out decrement mechanism, briefly indicating some of its uses for resource and topology discovery. In Section 3 we propose and analyze an algorithm for global multicast tree discovery. Section 4 includes comments on implementation and information exchange, and is followed by Section 5 wherein we discuss a framework for partial (i.e. local) topology discovery of multicast trees. In Section 6, additional use of the work is proposed and Section 7 discusses the advantages and shortcomings of previous work and contrasts these with our work. Section 8 concludes the paper.

2. Fan-out decrement mechanism

We propose a fan-out decrement mechanism for IP Multicast service, which supports the following three elements/behaviors:

1. A fan-out field in a multicast packet.
2. When a multicast packet traverses a router, corresponding to a fan-out point where the packet is replicated and forked out, the router decrements the fan-out field by one.
3. Multicast routers at fan-out points discard incoming packets whose fan-out fields have reached 0.

Note that these components are entirely analogous to those of the current TTL decrement mechanism. The main difference is the location where decrementing occurs: every router along the path of a packet for the TTL field while only routers corresponding to fan-out points in multicast distribution tree for fan-out field.

Consider the example shown in Fig. 1. Suppose member a multicasts a packet with its fan-out field set to 1. When the packet reaches fan-out node f, the fan-out field becomes 0 but the packet is duplicated and forwarded and will reach member b. Another duplicate packet will be forwarded in the other direction but is discarded at fan-out node h. Note that routers that are not fan-out points in the distribution tree, e.g. g, do not decrement the fan-out field or discard packets whose fan-out field is 0.

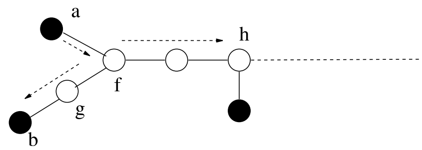

Fig. 1. Fan-out decrement mechanism illustration.

Table 1
Parallels between IP and IP multicast

IP	IP multicast
ICMP	IGMP
Traceroute	MTRACE
TTL decrement	Fan-out decrement

Clearly this mechanism serves as an intuitive and natural counterpart to the TTL decrement mechanism in IP. Table 1 summarizes parallels between IP and IP multicast components. Also note that this new feature is simple to implement and will not incur large overheads at routers. We envisage implementing fan-out decrementing in two ways: (1) changing native IP packet header and router functionality or (2) perhaps more realistically providing this as a service supported by IGMP [19] (see Section 4 for details).

The original purpose for the TTL decrement mechanism was to bound the life of packets in the network to circumvent the adverse effects of forwarding loops during routing transients. However, due to its simplicity and usefulness, the TTL decrement mechanism also can be used for scoping IP multicast packets as well as other applications associated with resource and path discovery, e.g. expanding ring search, traceroute [20]. We believe that, in the context of multicast service, the proposed fan-out decrement mechanism can play a similar role.

First, TTL scoping is to constrain how far a multicast packet can traverse within a multicast session by carefully choosing the TTL value. To see how the multicast scoping can be enhanced with the addition of the fan-out decrement mechanism, consider the case in Fig. 2(a) where member a wishes to send packets only to a set of node, $A = \{b, c, d\}$. Unless a sends repeated unicast transmissions to A, a can perform TTL scoping by setting TTL value to its maximum distance from a

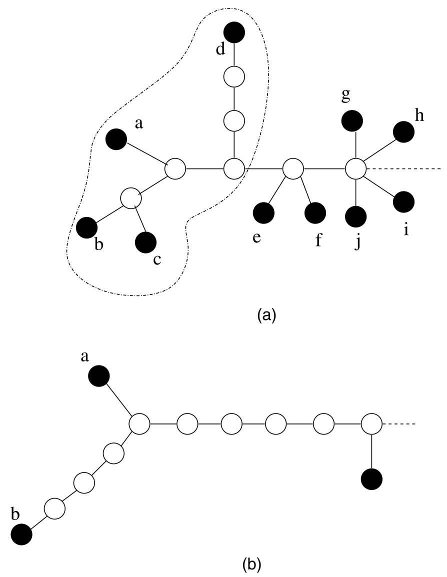

Fig. 2. Fan-out decrement mechanism usage illustrations.

to A, i.e. 5. However, the packets will eventually reach the other members, $\{e, f, g, h, i, j\}$. In addition to TTL scoping, setting fan-out value to its maximum fan-out distance from a to A, i.e. 2, turns out to be more efficient scoping since the packets will arrive only at A.

Second, suppose a member in a multicast session wishes to discover the existence of another one with a given attribute but close by. Currently, it may do so using expanding ring search: i.e. multicasting a sequence of query packets with increasing TTL until an appropriate reply is received. Note that we can save time and resources by using the fan-out field to perform an expanding ring search. The possible increase in efficiency for such a search, can be seen by considering the following of two members that are only one fan-out away but a large hop count distant from each other, shown in Fig. 2(b). Member a performs an expanding ring search based on the fan-out field, that is, sending a query packet with fan-out field set to 1. In this scenario, which might not be infrequent for sparse large-scale multicast sessions, member a can quickly identify a close member, b by the first query. Note that this type of resource discovery is applicable to *both* source and shared tree routing protocols. Also note that we are not arguing for the superiority of the fan-out decrement mechanism over the TTL one but proposing potential benefits when both mechanisms are being used together in IP multicast context.

Finally, as another useful application, we propose the discovery of shared multicast trees based on the proposed fan-out decrement mechanism. Our algorithm requires that each node acquire a *distance matrix* for the current session members, which is the path and fan-out distances of pairs of members. In order to do so, packets will need to carry two additional pieces of information, initial_TTL and initial_fan-out, corresponding to the initial values of the TTL and fan-out fields. Clearly with this information in hand, a receiver can immediately compute its path distance and fan-out distance, i.e. number of fan-out nodes traversed, from the source. In the next section we shall develop a tree discovery algorithm based on full and reduced distance matrices. In Section 4 we will discuss practical issues in efficiently acquiring and distributing the required distance information.

3. Tree discovery algorithm

We will consider several variations of the following basic problem: given the *distance matrix* associated with the members (i.e. end hosts) of a multicast session using a shared distribution tree, determine its physical topology.

3.1. Model and notation

We will use the physical multicast tree illustrated in Fig. 3 as a reference in discussing our model. [2] The end nodes, shown as solid black circles, correspond to members of the multicast session, while internal nodes, corresponding to network routers, are shown as white circles. [3] In the sequel we will refer to internal nodes where

[2] Throughout the paper, a multicast tree or a tree means a shared multicast tree, unless explicitly mentioned.

[3] In a multi-access LAN environment, an end node can be considered as a representative of all multicast members on the LAN, e.g. the one with the lowest IP address among members on the LAN.

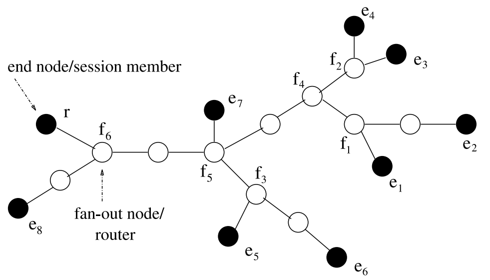

Fig. 3. Example of a physical shared multicast tree.

multiple copies of a multicast packet are created as *fan-out nodes.*

We define two types of distances between nodes on a tree. The *path distance* $d_p(m,n)$ between two nodes, m and n, corresponds to the number of links along the path between them. The *fan-out distance* $d_f(m,n)$ between two nodes, m and n, corresponds to the number of fan-out nodes on the path between them. Note that in the case where m or n are themselves fan-out nodes in the tree, the fan-out distance does not include m or n. For example, $d_f(f_1,f_2)=1$ in Fig. 3. We denote such path and fan-out distance as a tuple $d(m,n) = (d_p(m,n),\ d_f(m,n))$, e.g. for our example we have $d(e_2,e_6)=(8,4)$. Table 2 exhibits the *full distance matrix*, which contains the distances among all pairs of members in the multicast session shown in Fig. 3. Note that this table is symmetric.

When a node m is connected to a link l, m and l are said to be *incident* on each other. The number of links incident on a node m is called the *degree* of m. We say node n is *adjacent* to a node m if the nodes share a link.

The *logical tree* associated with a physical tree is obtained by eliminating internal nodes whose degree is 2. For example, Fig. 4 depicts the logical tree corresponding to the physical tree in Fig. 3. The nodes in a logical tree can be partitioned into *end nodes E*, whose degree is 1, and *fan-out nodes F*, whose degree is at least 3. In the sequel we let $|A|$ denote the cardinality of a set A. For a fan-out node $f \in F$ we let AE_f denote the set of its adjacent end nodes in the logical tree. Thus in our example, $AE_{f_1} = \{e_1, e_2\}$. Fan-out nodes which have at least 2 adjacent end nodes and only 1 adjacent fan-out node in a logical tree, is said to be a *border* fan-out nodes. We let *BF* denote the set of border fan-out nodes in the logical tree. For example, in Fig. 4, $BF = \{f_1, f_2, f_3, f_6\}$. The notion of a border fan-out node will be useful when we consider "reduced" distance matrices in Section 3.4.

Theorem 1. *A logical tree with at least two fan-out nodes has at least two border fan-out nodes, i.e. if* $|F| \geqslant 2$ *then* $|BF| \geqslant 2$.

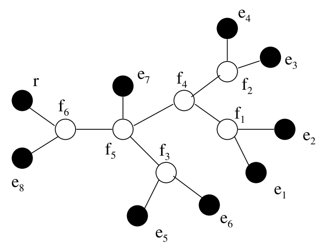

Fig. 4. The logical tree for our example.

Table 2
Full distance matrix for tree in Fig. 3

	r	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8
r		(7,4)	(8,4)	(7,4)	(7,4)	(5,3)	(6,3)	(4,2)	(3,1)
e_1			(3,1)	(4,3)	(4,3)	(6,4)	(7,4)	(5,3)	(8,4)
e_2				(5,3)	(5,3)	(7,4)	(8,4)	(6,3)	(9,4)
e_3					(2,1)	(6,4)	(7,4)	(5,3)	(8,4)
e_4						(6,4)	(7,4)	(5,3)	(8,4)
e_5							(3,1)	(3,2)	(6,3)
e_6								(4,2)	(7,3)
e_7									(5,2)
e_8									

Proof. Consider one of the longest paths in the logical tree. Since $|F| \geqslant 2$, such a path must include at least two fan-out nodes. We argue that the nodes adjacent to the the end nodes of the path must be border fan-out nodes. Suppose one of them is not a border fan-out node. Then there is another adjacent fan-out node which is not currently on the path. This means a longer path than the current one could be constructed and leads to a contradiction. □

Theorem 2. *A logical tree with $|E|$ end nodes has at most $|E| - 2$ fan-out nodes.*

Proof. This can be proven by constructing a tree which has a maximal number of fan-out nodes. First, note that a logical tree with $|E| + |F|$ nodes including end and fan-out nodes, has $|E| + |F| - 1$ links. Thus total degree sum of all nodes in the tree becomes $2(|E| + |F| - 1)$ since each link contributes 2 degrees. If we wish to construct a tree which has the maximal number of fan-out nodes in a tree, the degree of each fan-out node should be as small as possible, i.e. 3. The total degree sum of the tree will be then $3|F| + |E|$. Equating $3|F| + |E|$ with $2(|E| + |F| - 1)$ gives $|F| = |E| - 2$. □

Given an end node $r \in E$ we can consider the r-rooted logical multicast tree associated with a multicast session. We shall exhibit such trees with the root is at the top, and nodes that are equally distant from the root horizontally aligned at levels below it. Fig. 5 depicts the r-rooted logical tree for physical tree in Fig. 3.

With the introduction of the root, we can further partition the end nodes, E, and the fan-out nodes, F, according to their fan-out distances from the root. We let E_i represent the set of end nodes whose fan-out distance from the root is i. Similarly F_i denotes a set of fan-out nodes whose fan-out distance from the root is i. E_i and F_i are said to be at *level i*. Note that $i = 0, 1, \ldots, b$ where $b = \max_{m \in E} d_f(r, m)$. We define E_0 as $\{r\}$ and $F_b = \emptyset$. Fig. 5 shows the example of such a partition of end and fan-out nodes.

If a node p immediately precedes node c on the path from the root to c, then p is the *parent* of c

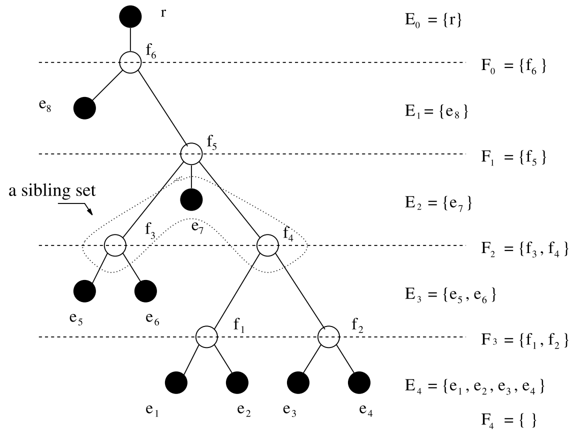

Fig. 5. The r-rooted logical tree for our example.

and c is the *child* of p. Nodes having the same parent are said to be *siblings*. We let a *sibling set* denote an *exhaustive* collection of siblings sharing the same parent. Note that for a given rooted logical tree there are several types of siblings:

- Type 1 (*mixed siblings*): An end node e at level i can be the sibling of a fan-out node at level i.
- Type 2 (*fan-out node siblings*): Fan-out nodes at the same level can be siblings.
- Type 3 (*end node siblings*): End nodes at the same level can be siblings.

In Fig. 5, the sibling sets $\{f_3, e_7, f_4\}$, $\{f_1, f_2\}$ and $\{e_5, e_6\}$ exemplify these types of relations respectively.

A node d is said to be a *descendant* of a node n, if n is on the path from the root to d. Note that from the above definition, n can be its own descendant. Given a fan-out node $f \in F$, we define a *reference* node of f, denoted by $r(f)$ to be any end node which is a descendant of f. Reference nodes will be used in checking sibling relations for fan-out nodes, since there is no explicit information for fan-out nodes in the distance matrix.

Note that the level ordering and filial relationships discussed above are always with respect to a given rooted logical tree. However, for simplicity we have not included the specified root in our notation.

3.2. Algorithm using the full distance matrix

In this section we discuss an algorithm to discover a tree given the full distance matrix. The algorithm includes two parts. Based on fan-out distances, one first discovers the logical tree, and then based on path distances, one determines the hop count lengths associated with links in the logical tree. The steps of the algorithm can be summarized as follows:

1. Logical tree discovery:
   - Select a root.
   - Perform a level ordering on end nodes, $E_i, i = 0, \dots, b$.
   - Perform bottom up discovery of $F_i, i = 0, \dots, b$ and sibling/parent relationships among nodes.
2. Physical tree discovery:
   - Perform bottom up discovery of path distances associated with the logical tree's links.

Below we outline the details associated with these steps.

3.2.1. Logical tree discovery

The first task is to select a root for the logical tree. In general any node could be selected, however since we intend the discovery algorithm to be carried out in a distributed fashion at each end node we shall assume without loss of generality that each end node considers itself to be the root of the tree. We let $r \in E$ be the root for our ongoing example. Next, we partition the end-nodes into sets E_i, $i = 0, \dots b$, based on their fan-out distances from the root. This is done by checking r's row in the distance matrix.

The key task in the logical tree discovery step is to progressively identify complete sibling sets in a bottom up fashion. Note that each sibling set is associated with a unique, previously unknown, parent fan-out node at a higher level of the logical tree. Thus we can progressively determine not only F_i, $i = 0, \dots, b-1$ but the filial relations among the rooted tree's nodes. We shall start at the bottom, setting $i = b$. The key step will be at each level i, to discover complete sibling sets among E_i and F_i and create the associated set of parent fan-out nodes, F_{i-1}, at the next level. The following lemma will enable us to check whether two nodes in $E_i \cup F_i$ are siblings.

Lemma 1 (Sibling checking lemma).

1. *Suppose* $e \in E_i$ *and* $f \in F_i$ *then they are siblings iff*
   $d_f(e, r(f)) - d_f(f, r(f)) = 2.$
2. *Suppose* $f_a, f_b \in F_i$ *then they are siblings iff*
   $d_f(r(f_a), r(f_b)) - d_f(f_a, r(f_a)) - d_f(f_b, r(f_b)) = 3.$
3. *Suppose* e_a, $e_b \in E_i$ *then they are siblings iff* $d_f(e_a, e_b) = 1$.

The proof of the lemma is straightforward. In the first case, e and f are siblings iff $d_f(e, f) = 1$, so the lemma follows by noting that we can compute $d_f(e, f)$ based on f's reference node $r(f)$ as $d_f(e, r(f)) - d_f(f, r(f)) - 1$. In Fig. 6 sibling nodes f_4 and e_7 exemplify this case. For the second case, note that f_a and f_b are siblings iff $d_f(f_a, f_b) = 1$. The lemma follows by computing this distance based on reference nodes for associated fan-out nodes, i.e.

$$d_f(f_a, f_b) = d_f(r(f_a), r(f_b)) - d_f(f_a, r(f_a)) - d_f(f_b, r(f_b)) - 2.$$

Siblings f_3 and f_4 in Fig. 6 exemplify the second case. The final case is clear and can be easily

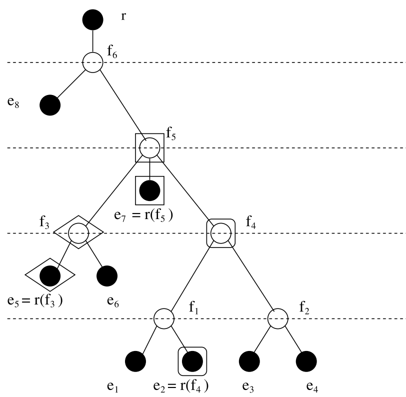

Fig. 6. Illustration of sibling checking criteria.

checked using e_a's (or e_b's) row in the distance matrix.

In order to discover complete sibling sets among the nodes we let $C = E_i \cup F_i$ denote the set of nodes that need to be considered. Select any node $c_1 \in C$ and determine the set of *all* of its siblings S_1, including c_1, by checking each of the remaining nodes in C using Lemma 1. Now let $C := C \setminus S_1$ and proceed iteratively until there are no more nodes in C. Suppose this process terminates after k steps, then k disjoint sibling sets $S_1, \ldots, S_k$ are obtained. For each of these, generate a parent node f_j, $j = 1, \ldots, k$ and place it in the set F_{i-1} of fan-out nodes at the next level up. Also define the reference node $r(f_j)$ for each parent, f_j, to be any end node which descends from f_j. At this point one can proceed in discovering siblings and parents at the next level up. This procedure continues until the logical tree topology is determined.

3.2.2. Discovery of path distances of logical links

Once we have identified the logical tree, we need only to find path lengths associated with its logical links to determine the physical tree. The key idea is captured by the following lemma, which determines path distances of logical links between a border fan-out node $f \in BF$ and its adjacent end nodes AE_f.

Lemma 2. *Suppose $f \in BF$, $m, n \in AE_f$ and $k \in E$, $k \neq m, n$ then*

$$d_p(m,f) = [d_p(m,n) + d_p(k,m) - d_p(k,n)]/2,$$
$$d_p(n,f) = [d_p(m,n) - d_p(k,m) + d_p(k,n)]/2.$$

The proof of this lemma follows directly by decomposing path lengths into their constituent components—consider Fig. 7. Moreover for any additional node, $e \in AE_f \setminus \{m,n\}$, the path distance $d_p(e,f)$ can be computed to be $d_p(m,e) - d_p(m,f)$. Observe that to determine the lengths of the logical links from a border fan-out node f to all its adjacent end nodes AE_f we only require two rows of the distance matrix, where at least one is associated with one node in AE_f.

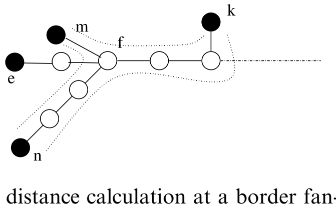

Fig. 7. Path distance calculation at a border fan-out node f.

Table 3
Path distance matrix for the tree in Fig. 8

	r	f_1	f_2	e_5	e_6	e_7	e_8
r		6	6	5	6	4	3
f_1			2	5	6	4	7
f_2				5	6	4	7
e_5					3	3	6
e_6						4	7
e_7							5
e_8							

Note that for any rooted logical tree, if $f \in F_{b-1}$ then $f \in BF$. Thus by Lemma 2 all the lengths for logical links at the bottom level can be computed. In order to proceed systematically in a bottom up fashion, we propose to prune the tree and update the path distance matrix. At level i, all links and end nodes E_i whose distance to their parents have been computed are pruned. Then all fan-out nodes at level $i-1$, i.e. F_{i-1}, became end nodes at level $i-1$. In this pruned tree, all $f \in F_{i-2}$ are border fan-out nodes, which guarantees that the path distance calculation step can again be performed for level $i-1$.

As a result of pruning, the path distance matrix for the new tree must be generated. This is done by eliminating entries associated with all the pruned end nodes, and adding a new entry, for each fan-out node f that becomes an end node of the new tree. Table 3 is the path distance matrix for the pruned tree in Fig. 8.

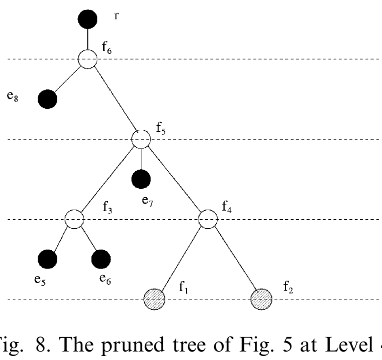

Fig. 8. The pruned tree of Fig. 5 at Level 4.

3.3. Computational complexity

The computational complexity for the proposed algorithm can be roughly evaluated as follows. The level ordering step is $O(|E|)$. The bottom up step in the logical topology discovery phase can be shown to be $O(|E|^2)$. Indeed there are at most $|E| - 2$ fan-out nodes in the tree by Theorem 2 and determining siblings associated with each parent fan-out node has a cost of at most $|E|$. Path distance computations to obtain the physical topology are also quadratic. So the overall computational cost is $O(|E|^2)$.

3.4. Reducing the required distance information

There is in fact a large amount of redundant information in the distance matrix. This motivates us to ask the following question: What is the minimal required distance information in order to discover a tree? To answer this question, we will define our unit of information as an end node's entire row table which includes path/fan-out distances from the end node to all other end nodes in a tree. Let NE denote the set of end nodes whose row tables are available when performing topology discovery. Our goal is to find a reduced set NE such that the topology of the multicast session can still be determined. Note that the algorithm described in Section 3.2 requires the full distance matrix, i.e. $NE = E$.

Theorem 3. *Given a shared multicast tree with $|F|$ fan-out nodes the following conditions on the set NE of available rows in the distance matrix are sufficient to allow topology discovery*:

1. *If $|F| = 1$ then $|NE| \geqslant 2$.*
2. *If $|F| \geqslant 2$ then NE should include at least one node in the set of end nodes AE_f associated with each border fan-out node $f \in BF$.*

Proof. Consider the first case. If $|F| = 1$, the discovery of the logical topology is straightforward, i.e. all nodes are 1 fan-out distant from each other. This can be determined based on a single row table. Note that by Lemma 2 if two row tables are available, one can compute all path distances from a fan-out node to its adjacent end nodes. This establishes the condition for the first case.

Now suppose that NE includes one node from each set AE_f associated with border fan-out nodes $f \in BF$. We show that the logical topology can be determined as follows. Select any node $r \in NE$ as the root and perform a level ordering on end nodes based on r's row table. Note that during our bottom up phase, we will be able to assign a reference node in NE to each generated fan-out node, since every fan-out node in a rooted logical tree, has at least one border fan-out node as its descendant. This guarantees that all the required information is available to use Lemma 1 for sibling checking.

Next we show that subject to given conditions, the physical topology can also be discovered. Note that by Theorem 1, if $|F| \geqslant 2$ then $|NE| \geqslant 2$. Recall that by Lemma 2, in order to know the path lengths associated with logical links from a border fan-out node, e.g. f, to its adjacent end-nodes, we only need two row tables of which at least one node should be in AE_f. Since NE contains at least one in AE_f, and $|NE| \geqslant 2$, all path distances to f can be computed. The path length computation can once again be carried out by pruning, starting from the bottom level to the top. □

Note that the computational complexity of topology discovery based on the reduced distance matrix remains $O(|E|^2)$.

4. Obtaining distance information

In this section we discuss implementation issues concerning how members of the multicast session can selectively acquire sufficient distance information to discover the topology of the multicast tree. The elements necessary in our proposed framework are:

1. Fan-out decrement mechanism.
2. Initial path/fan-out field in packets for allowing a receiving host to obtain distance information from the sender to itself.
3. *Bidirectional* shared multicast routing protocols, e.g. CBT and Border Gateway Multicast

Protocol (BGMP) [21] for preserving path symmetry between members.

Note that TTL decrement mechanism operates on every IP packet. Similarly, we can envisage that the fan-out decrement mechanism could be applied to every multicast packet. However, this would need an additional fan-out field in the IP packet header while requiring modifications to all routers. Alternatively, the fan-out decrement mechanism can be implemented as a special feature in IGMP [19]. In this case, applications wishing to use fan-out decrementing, will encapsulate their packets within IGMP packets. Then, the fan-out decrementing would be performed only when desired, i.e. not for every multicast packet. This new feature would be simple to implement and will incur fairly low overheads at routers.

To create shared multicast trees, *unidirectional* multicast routing protocol such as PIM-SM [22] might be used. However, note that PIM-SM is not applicable to our model since in *unidirectional* multicast protocols the sender's packet goes to the core first and then the core multicasts it to the others. Thus there is no way for each member to acquire other members' distance information. In contrast, in *bidirectional* multicast routing protocols, members can communicate with each other without going through the core since packets can travel both up toward the core and down from the core [18].

Assuming that the above requirements are satisfied, first, we discuss how each member can obtain the full distance matrix. Suppose every member periodically multicasts a *heartbeat* packet to the whole group. The role of the heartbeat packet is two-fold: (1) it serves as an indication of the liveness of the sending host, which is necessary if the algorithm is to adapt to changing membership or topologies; and (2) it enables receiving members to obtain their fan-out/path distances from the sender. Note that senders which persistently multicast data packets to the session may not need to send heartbeat packets, as long as initial values for the TTL and fan-out fields are included in the IP multicast packet's header. Whenever a member receives a heartbeat from other members, the member can build/update its row in the session's distance matrix, where each member is identified by its IP address. In addition to periodically sending heartbeat packets, each member becomes a *reporter* and periodically multicasts a *report* packet to the session which contains its own row table. Thus, eventually each session member would have access to the full distance matrix.

Theorem 3 suggests that it would suffice for only one node among adjacent members of each border fan-out node to generate report packets. The above approach has two advantages over the full distance distribution method. First, it reduces the number of reporters in a session, which results in significant reduction of communication overheads since report packets can be large relative to heartbeat packets. Second, it can also reduce memory storage space required at end-hosts. In order to enable this type of reporting, one must however identify border fan-out nodes, and then select a unique reporter for such a node. This in itself requires that the network topology be known a priori, which is not practical.

As a compromise between full distance matrix distribution and the impractical second approach discussed above, we propose the following rules to determine which end hosts should serve as reporters:

Rule 1: A member will serve as a reporter if there is at least one other member which is 1 fan-out distant from it and it has the smallest IP address among members within 1 fan-out distance.

Rule 2: A member will serve as a reporter if all other members in a session are 1 fan-out distant from it and it has the largest IP address among members within 1 fan-out distance.

Note that the first rule guarantees that there will be a reporter selected from set of adjacent members to a border fan-out node—there may also be some additional reporters. The second rule ensures that if the tree has but one fan-out node, there will be at least 2 reporters. Thus with these two rules enforced, the sufficient conditions stated in Theorem 3 will be satisfied.

Note that these rules can be applied by nodes in a decentralized fashion in that they need only to check their own row table without any computation. This approach would of course reduce network traffic to acquire the required distance information. Also note that in this context the minimum number of reporters is 2 while the the maximum number of reporters is $\lfloor |E|/2 \rfloor$.[4] In general the communication complexity to acquire the distance matrix would be $2|E|$ multicast messages, i.e. a heartbeat and report packet per session member, where the size of heartbeat packets is O(1) while that of reports is O(|E|).

5. Local topology discovery framework

If a multicast session involves a huge number of members, the proposed global topology discovery scheme may not be workable. In particular, the communication, computation and storage overheads may be unwarranted.

Note also that since each row in the distance matrix contains each members' IP address, for large multicast trees this may include a lot of data, eventually requiring reports to be partitioned across several packets.[5] Moreover, in a large scale multicast session, members may not be interested in discovering the entire distribution tree. Instead they may only be interested in a local view of the multicast tree's structure. This is, for example, the case in the context of applications for local loss recovery where members only wish to identify other members within a given neighborhood. Thus it would be advantageous if the proposed framework could also be used to discover a restricted local topology while reducing the overheads associated with acquiring this information.

5.1. Concept

Let us consider an instance of this problem for a session member $r \in E$. Let a *neighborhood* N_r be the set of members that share a particular attribute, including r itself. Note that there is quite a bit flexibility in defining N_r. For example the neighborhood could correspond to FN_r^k, the set of members within the k fan-out scope from r including r itself, or the set of members that serve as DNS servers and are in FN_r^k. Given such a neighborhood, we define the *induced physical and logical trees* as follows.

Definition 1. Given a neighborhood $N_r \subset E$ of a node $r \in E$ in a multicast tree, we let the N_r *induced physical tree* be the subtree connecting r to the members of its neighborhood N_r. We define the N_r *induced logical tree* as the logical tree associated with the N_r induced physical tree.

For example, consider the neighborhood $N_r = \{r, e_5, e_8\}$ of r in a physical multicast tree shown in Fig. 9. The region that has been outlined corresponds to the physical tree induced by N_r while Fig. 10 depicts the N_r induced logical tree.

Note that an N_r induced logical tree simply shows the logical relationship among members in N_r, and it might include logical links that hide fan-out nodes in the global multicast tree. For example, the logical link from f_6 to e_5 in Fig. 10 actually represents three physical links and two fan-out nodes.

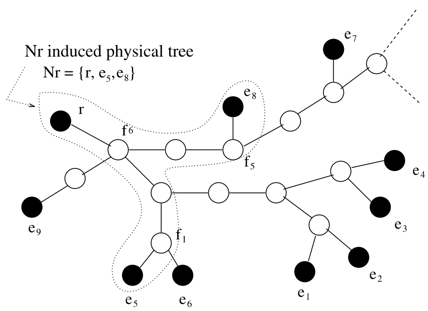

Fig. 9. A physical multicast tree.

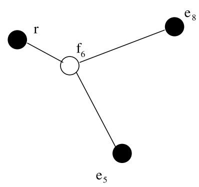

Fig. 10. The N_r induced logical tree ($N_r = \{r, e_5, e_8\}$).

[4] The notation, $\lfloor \rfloor$, is a floor operator.

[5] In order to reduce communication overheads, one might consider reports that include only incremental changes in data. This must, however, be done with care in a dynamic scenario as new members need to eventually acquire sufficient information to discover the tree.

Definition 2. Given a neighborhood $N_r \subset E$ of a node $r \in E$ in a multicast tree, the *local multicast topology discovery of* N_r is defined as determining the N_r induced logical tree topology, as well as path/fan-out distances for its logical links.

Local topology discovery can be based on an N_r *restricted* distance matrix including only row and column entries associated with the nodes in N_r. This problem can be viewed as a restricted version of the global topology discovery problem presented in Section 3. It is relatively easy to see that one can, with some care, apply the same methods developed for global topology discovery in this context.

We propose to perform local topology discovery by first determining the N_r induced logical topology applying the algorithm in Section 3.2.1. In this step, we in fact determine the subtree induced by N_r on the *global logical topology*. This is illustrated in Fig. 11 for the local topology discovery problem associated with FN_r^3 in the multicast session Fig. 9. Note that the subtree enclosed in the dashed line need not be the desired N_r induced logical tree. In particular, the subtree obtained by using our previous algorithm on the restricted set may include fan-out nodes, e.g. f_3 and f_4 in the above example, which would not be part of the N_r induced logical topology, see Fig. 12. Once such nodes are pruned, the structure of the N_r induced logical tree has been discovered along with the fan-out distances associated with its logical links.

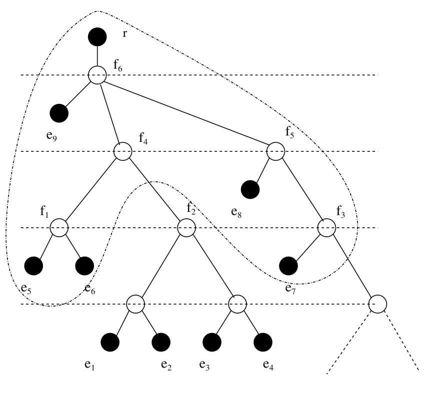

Fig. 11. The r rooted logical tree of Fig. 9.

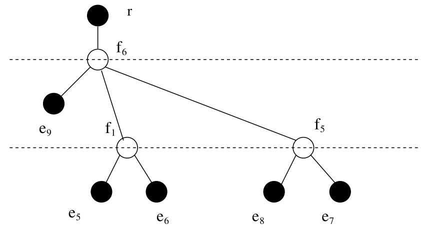

Fig. 12. The FN_r^3 induced logical tree.

Next, based on Lemma 2, one can identify the path distances of the logical links in the N_r induced logical subtree. Note that certain path metrics would not, and in fact can not, be identified based on the N_r restricted distance matrix. For example, node f_4 is not present in the induced logical subtree, and thus the path lengths f_1 to f_4 and f_4 to f_6 would not be determined, however the overall path metric associated with the logical link from f_1 to f_6, can be identified.

In summary, discovering an N_r induced logical tree's topology and the associated logical links' distances requires basically the same steps as discussed for the global case. It should be clear that the computational complexity of local topology discovery is quadratic in the size of the neighborhood, and storage requirements would also depend on the size of the the neighborhood.

In principle a neighborhood can be any set of members sharing a particular attribute. However, below we will focus on local topology discovery, i.e. that associated with neighborhoods having spatial proximity on the multicast tree. Thus we will define both fan-out and TTL scoped neighborhoods for a given node. We let TN_r^l denote the set of members in a multicast group that are within an l limited TTL scope from r including r itself. In general one can define a jointly scoped neighborhood, e.g. $N_r = FN_r^k \cap TN_r^l$, for each node in a network and proceed to discover the induced logical trees based on restricted distance matrices.

5.2. Obtaining restricted distance matrices

The remaining question is how each node would acquire the restricted distance matrix associated with its k fan-out and l TTL scoped neighborhood. Depending on the application, we can envisage the following two cases for local topology discovery. For some collaborative applications, *every* member in a session may need to have a local view of its neighborhood, each with the same uniform k fan-out and l TTL scope. By contrast, other applications might only require *some* nodes to acquire their own local topology associated with possibly heterogeneous fan-out/path scopes. Considering the above two cases, here we propose two schemes for acquiring the restricted distance matrix.

5.2.1. Uniform local topology discovery

The goal of the first scheme is to enable *each* member, say r, to discover its neighborhood, $N_r = FN_r^k \cap TN_r^l$ with a uniform k and l. The following simple protocol suffices:

1. Each member periodically sends heartbeat packets with the fan-out scope set to $2k-1$ and the TTL scope set to $2l-2$.
2. Each member periodically sends a report packet with k and l set as the fan-out and TTL scopes respectively.

The idea underlying this scheme is quite simple. First, each node r should receive reports from all members of its neighborhood, thus report packets should be scoped as indicated above. Second, since an N_r restricted distance matrix contains path and fan-out distances among all pairs of members in N_r, they have to know of each other's existence and the associated distances. Note that $2k-1$ and $2l-2$ are the maximum possible fan-out and TTL distances between members in $N_r = FN_r^k \cap TN_r^l$. Thus it should be clear that the proposed fan-out and TTL scopes on heartbeat packets ensure that the N_r restricted distance matrix acquired by a node r is complete. Note that we have assumed an a priori uniform selection of k and l for all nodes. This poses the question of how they might be "optimally" chosen and whether they might be selected in a non-homogeneous decentralized fashion. This would of course depend on applications.

Assuming nodes share information in this fashion, one can significantly reduce the communication overhead associated with topology discovery, in terms of the number of heartbeat and report packets seen on *any* link in the multicast tree and the size of the report packets. Indeed, although the same total number of packets, $2|E|$, will be sent as in the global discovery case, these packets are scoped and hence will not be seen by all links and members. In particular, a rough estimate for the number of messages seen by a member would be the size of its $2k-1$ fan-out and $2l-2$ TTL scoped neighborhood. Similarly the size of report packets would is no longer be $|E|$ but proportional to the size of the neighborhoods.

5.2.2. Non-uniform local topology discovery

The above scheme may incur heavy communication overhead in the case where topology information is not frequently required and not necessary for all nodes in a session. In such cases, we propose the following scheme which allows a single node to discover its local topology within a predefined fan-out/path distance when desired. To do so, we introduce a 32 bit *requester ID field* in heartbeat packets. Depending on the content of the field, we can classify heartbeat packets into two types: a *request heartbeat* or a *normal heartbeat*. In a request heartbeat, the requester ID field is set to 0 by a *requester* which wants to discover its local topology. A normal heartbeat is generated by a *responder*, i.e. a node that receives a request heartbeat. When a responder generates a normal heartbeat, it places the requester's IP address in the requester ID field. [6]

Let r be a requester and suppose its aim is to acquire its restricted $N_r = FN_r^k \cap TN_r^l$ distance matrix. We propose the following mechanism:

1. A requester, r, multicasts a request heartbeat setting k and l as scoping fan-out and path distance parameters respectively.
2. Each responder of r, say a, multicasts a normal heartbeat with its fan-out scope set to $d_f(r,a) + k - 1$, TTL scope set to $d_p(r,a) + l - 2$, and r's IP address in its requesterID field.

[6] Note that when a node receives a heartbeat packet, it can determine if the heartbeat packet comes from the requester by checking if the requester ID field is set to 0, and if so, it also can extract the requester's IP address from the source address of the heartbeat packet.

3. Based on the requester ID fields of the received heartbeat packets, each responder of r builds its own row table whose entries are composed of r and responders of r.
4. Each responder of r unicasts a report packet to r.

In this scheme when there is no requester, no traffic is injected into the network, which in turn, may enormously reduce communication overheads. Note that the scoping parameters in Step 1, suppress packet injection from other members but only r's responders, which indeed are members of r's neighborhood. For example, consider the case where there is one requester, r, in Fig. 13. Only a, q and r will generate packets while b and o will discard the normal heartbeat packets from r's responders, e.g. a or q.

In Step 2, the selection of scoping parameters of each responder is such that fan-out/path distance information among all pairs of members in N_r is eventually obtained. It is clear that by setting the fan-out scope to $d_f(r,a)+k-1$ and the path scope to $d_p(r,a)+l-2$, a's heartbeat packets can reach all members in N_r (see Fig. 14 for the fan-out distance case). This choice of scoping parameters instead of $2k-1$ and $2l-2$ further suppresses the scope of the normal heartbeat and thus minimizes the communication overheads.

Note that in Step 3, each responder of r would include only data associated with nodes in r's neighborhood. In particular, the requester field enables a responder to distinguish more than one ongoing topology discovery attempts and makes our proposed scheme work well even in the presence of multiple requesters whose neighborhoods overlap. For example, suppose that there are two concurrent requesters r and b in Fig. 13. In this case a will multicast two differently configured normal heartbeats associated with r and b. Also note that when a builds a report packet to b, it would not include q entry since q is not a responder of b. This feature keeps the size of a report packet proportional to the size of the requester's neighborhood.

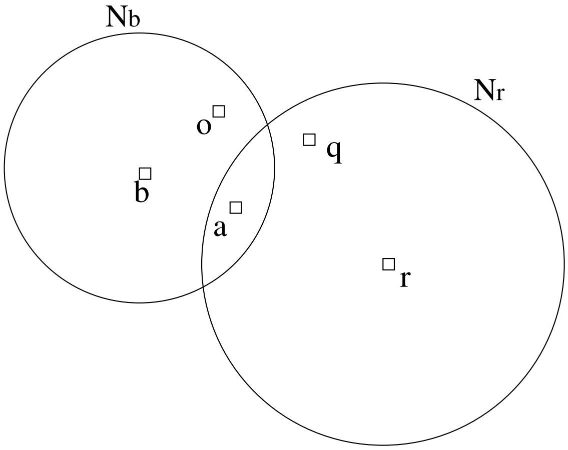

Fig. 13. Illustration of multiple requesters.

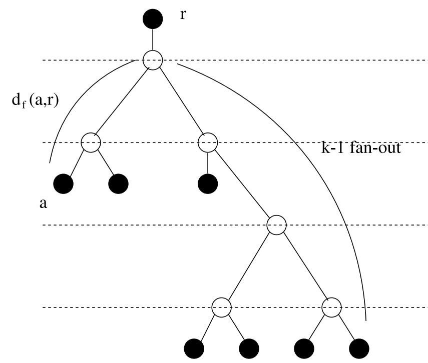

Fig. 14. Fan-out scoping parameter selection.

Lastly, the report will be sent to r via unicast further reducing communication overheads.

In addition to the basic mechanism described above, some more detailed issues need to be addressed. In the above scheme we make two assumptions: (1) there is no packet loss, e.g. heartbeats or reporters and (2) each responder knows when it has received all the required information to build its own row table. A simple way to handle these problems is to repeat the above scheme several times. Then eventually a requester can obtain its restricted distance matrix.

6. Annotated trees

So far, the main role of heartbeat packets is to enable each host to obtain fan-out/path distance information from the others. In this section, we

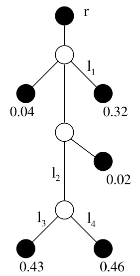

Fig. 15. A tree annotated with packet loss rate.

briefly describe how additional information in a heartbeat can be beneficial for some one-to-many multicast applications, e.g. local loss recovery or locating approximate problematic links.

Consider the case that one sender persistently multicasts packets and each receiver can evaluate its own performance metrics, e.g. packet loss rate or bottleneck bandwidth [9]. By combining these performance values exchanged through heartbeats with the proposed topology discovery scheme, one can obtain an *annotated tree*, i.e. a tree whose leaves have associated performance metrics. Note that obtaining annotated trees only slightly increases the size of heartbeat packets with no additional packet exchanges. Fig. 15 exhibits an example of a tree annotated with packet loss rate.

This tree might be useful to a local loss recovery mechanism in determining a "good" (close and capable) *helper* from which a node can obtain lost packets [2]. Furthermore, this tree can also help to approximately locate the problematic links [9]. [7]

For example, based on the annotated tree in Fig. 15, it is easy to determine that a link l_1 is seeing a high degree of packet loss. However, it is not clear how to differentiate the quality of links, l_2, l_3, l_4 since there are several scenarios are possible, e.g. (1) only l_2 is bad or (2) both l_3, l_4 is bad etc. If accurate estimation of each links' packet loss rate is desired, the approach in [23] could be used with the topology information provided by our framework.

[7] Here note that considered links are logical.

7. Related work

In this section, we discuss the pros and cons of existing work on multicast distribution tree discovery and the approach proposed in this paper. Our intent is to find in which environment each approach fits best by identifying its advantages and shortcomings rather than arguing the superiority of our approach over existing ones. Existing approaches to multicast distribution tree discovery can be classified into two types: those based on end-to-end measurements [9,11], and those requiring the help of intervening network nodes [8].

The key idea underlying the first approach is that receivers sharing common paths on the multicast tree associated with a given source will see correlations in their packet losses. Thus based on the shared loss statistics for transmitted probe packets one can attempt to infer the multicast tree. This elegant approach to the problem is particularly advantageous in that it requires no support from internal nodes. However, since this approach is based on the loss of packets, a source needs to send a large number of *probe* multicast packets even if the goal is to discover the topology of a small scale multicast tree. The lower the packet loss rate for links is, the larger the number of probe packets is needed. Furthermore, it potentially suffers from significant communication overheads required to periodically gather large amounts of loss data so as to adapt to changing memberships or topology, and processing overheads to assemble and perform the inference step. This is currently conceived as a centralized approach whose accuracy is unlikely to scale nicely. The approach assumes network links have steady state loss characteristics, which may or may not be realistic on the time-scales during which loss data are collected. A final point is that the approach permits identification of the logical multicast topology rather than the actual physical topology. This means that a session member that is at the end of a long path with no intervening fan-out points, would see this section of its path collapsed to a single logical link. In practice this may or may not be an appropriate abstraction of the actual topology. The key advantage of this approach lies in its applicability to inferring multicast trees without requiring modifications to, or the help from, internal nodes.

Compared to the first approach, our approach has a number of advantages. To name a few, the communication overhead is low since it requires at most $2|E|$ multicast packets of size $O(|E|)$. Its computation complexity is low as much as $O(|E|^2)$ and it is quickly adaptable to tree changes since distance information will be immediately seen by heartbeat packets.

The second approach to multicast topology discovery which has the above-mentioned desirable characteristics is based on using the MTRACE feature currently implemented in the IGMP protocol [9]. MTRACE enables tracing the path from a source to a destination on a given multicast distribution tree [8]. A query packet is sent from the requester to the last multicast router (on the distribution tree) prior to a given destination. This query is then forwarded hop-by-hop along the reverse path from the "last-hop" router to "first-hop" router, i.e. that to which the source is attached. While the query packet traverses the tree, each router adds a response data block containing its interface addresses and packet statistics. When the query packet reaches the first-hop router it is sent back to the requester via unicasting or multicasting.

Note that an MTRACE query provides full information, i.e. interface addresses and performance characteristics, but *only* for *one* path from a multicast source to a given destination. Thus if all members wish to know the full multicast topology for a given source, each receiver would send a query packet to its last-hop router, and query responses should be *multicast* to the entire group. Then the reconstruction of the full multicast topology is achievable since each packet includes a stack of interface addresses for nodes along the path from the source and the destination. Note that all query traffic would visit the first-hop router which would in turn generate multicast responses. Due to this focussed load, in a large-scale multicast session, this approach may not scale. By comparison, in our approach, there is no single focussed, or central point, which leads to a more decentralized mechanism. Key advantages of the second approach are that it provides full information on the multicast topology based on currently available IGMP features.

In contrast, our approach is based on introducing a new fan-out decrement mechanism in IP multicast, which is not currently available. However, as pointed out in Section 2, it is simple to implement and provides a generic service which has broad applicabilities, i.e. not only topology discovery but also efficient scoping within IP multicast context. Furthermore, by implementing this as a special feature of IGMP, as proposed in Section 4, fan-out decrementing need only be supported when needed, thus incurring low overheads at routers. Note that this overhead at routers may be 'lighter' than that of MTRACE since MTRACE inserts each interface's address as well as packet loss statistics.

Note that while the first approach is strictly based on using end-to-end measurements, the second relies heavily on special services at routers, thus from the perspective of required network support these are two extremes of the spectrum. Also the first approach identifies the logical topology while the second determines the physical topology including interface addresses of routers. Note that our approach lies somewhere in their midst, requiring light weight cooperation from multicast capable routers (i.e. fan-out decrementing) and cooperation among members in the session to identify the physical topology (without internal interface addresses).

One limitation of our approach lies in its narrow applicability to bidirectional shared multicast routing protocols since it requires a path symmetry property among members. However, bidirectional shared multicast routing protocols are likely to become increasingly crucial, as a number of large scale multicast applications are emerging. First, it is generally considered that shared tree routing is more efficient than source tree routing for large scale multicast applications such as distributed interactive simulations [24] where each member is both a sender and a receiver. This is because source tree routing maintains source as well as group specific state information at routers. Second, once shared tree routing is determined to be used, unidirectional routing protocols are inefficient for multicast scoping and communications among neighborhoods since every multicast packet should visit the core in first. The larger are multicast sessions and the more is the demand for local resource discovery, the larger communication overheads will be incurred in unidirectional shared multicast routing protocols. Reflecting these observations, the long term inter-domain routing solution, BGMP [21] currently under development, constructs bidirectional shared trees.

Finally note that while existing work focus on *global* multicast *topology* discovery, our approach provides a general framework for *resource* discovery within a session and its associated *topology* discovery, which allows not only *global* but also *local* topology discovery. This comes from the fact that our approach is based on interactions among members.

8. Conclusions

The proposed framework for resource discovery and its associated global and local topology discovery of shared multicast trees has significant advantages over current approaches, particularly in terms of simplicity, adaptability and scalability. It is based on the addition of a new fan-out decrement mechanism to IP multicast functionalities. However this new service is simple to implement, and provides an efficient way of scoping in the context of IP multicast sessions. Furthermore, as the use of multicast sessions and applications becomes increasingly widespread, the possible benefits resulting from the availability of topological information may warrant the addition of this mechanism.

In this paper, first we propose an algorithm, which can discover the topology of the shared multicast tree based on a full distance matrix, with the analysis of computational complexity. Second, we provide sufficient conditions to achieve the same result with a reduced distance matrix. Third, we show how reduced distance information could be acquired efficiently by exchanging a small number of multicast packets with an analysis of explicit communication overheads, i.e. the minimal number of packets injected in the network and the size of the packets. Fourth, we consider concepts in the context of local topology discovery enabling nodes to discover the distribution tree within their fan-out and TTL scoped neighborhoods. Furthermore, we discuss practical issues for acquiring distance information in both uniform and non-uniform manner. Finally, we present an annotated tree concept for possible applications, e.g. identification of congested links.

We believe a number of large multicast applications which involve large amounts of interaction among members, may benefit from the proposed approach. The applications that we have in mind for these techniques, involve enhancing network utilization by partitioning or clustering multicast session members, distributed algorithms based on local topology, and methods for assessing the actual network resource costs to support multicasting. In addition, another interesting topic can be more scalable approaches to global topology discovery involving the use of local discovery combined with hierarchical distribution of topology information.

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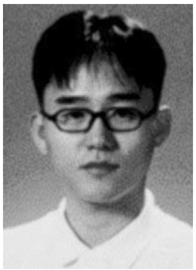

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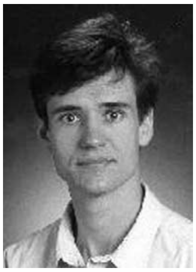

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