A Cost-Based Approach for Analysing the Overheads of Multicast Protocols in Non-Strictly Hierarchical Networks

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Abstract: In this paper we study the properties of protocol independent multicast (PIM) in non-strictly hierarchical network environments. In particular, we investigate the cost (overhead) behaviour of the PIM protocols i.e., sparse mode (PIM-SM), dense mode with flood and prune mechanism (PIM-DMFP), dense mode with state refresh (PIM-DMSR), and source specific multicast (PIM-SSM). By assuming that the links in the networks are symmetrical, we assign equal values to both up and down links and then specify analytical models to evaluate the performance of the protocols in static multicast group scenarios. We determine the overhead of setting up the protocols in terms of the number of links a packet traverses. We generate numerical results to analyse the effectiveness of our model. Our results confirm that the PIM-SM protocol remains superior over the other three variants in most mean group sizes

Keywords: Cost behaviour, mean group sizes, non-strictly hierarchical network, protocol independent multicast, symmetrical links.

1. Introduction

The volume of multicast traffic has been growing because of the emergence of video-based applications. The significant interest in Internet protocol TV (IPTV) services, distribution of media-rich financial services or enterprise multicast services, and multicast backhaul over a metro networks are driving the need to consider more scalable and cost-effective models for delivering multicast services in different networks [1]. As multicast applications, such as gaming, distributed interactive simulation to software distribution, webcasting, IPTV and multimedia collaboration, gained popularity, and as the number of networks with different service need to merge multicast flows over shared infrastructure, the demand for deploying multicast service in different networks is rapidly increasing.

The next-generation multicast over a virtual private network (GN MVPN) [3] as compared to Draft-Rosen [2] provides the flexibility to build scalable and effective cost models for an MVPN service [4]. Different applications have different bandwidth/latency requirements, therefore when costs are set to reflect actual network resource consumption; they help to reduce market distortion, which can result in efficient and equitable resource allocation.

As many multicast based applications are increasing, the deployment of IP multicast at reasonable benefits (e.g. bandwidth savings) [5], [6] continues to gain increasing popularity among researchers, multicast designers and network integrators. This has led to an increase in the number of publications in the literature [8] and several variants of PIMs have emerged. These include PIM-dense mode with state refresh (PIM-DMSR) [7], PIM-dense mode with flood and prune (PIM-DMFP) [7] and PIM-source specific multicast (PIM-SSM) [9], [10], [11]. As these different variants of the PIMs, include PIM-SM [23] are deployed in different networks to enhance group communications at a price, we are therefore motivated to design a cost model to evaluate these protocols with a view to providing useful information to network integrators, users, and the network community.

The rest of this paper is organised as follows. We review related work in Section 2. Section 3 briefly presents the operational features of the PIM protocols. Section 4 discusses the cost behaviour of the protocols in a non-strictly hierarchical network, while the performance cost metric is briefly discussed in Section 5. In section 6, we specify a cost model to quantify the PIM protocols as well as generating numerical results using C#. We analyse the performance of the PIM protocols in Section 7. Section 8 concludes the work and sets the direction for further research work.

2. Related Work

There has been a growing literature on cost computations, allocation, and pricing in communication networks. In [28], the authors reviewed the IPTV, which has been a preferred alternative to broadcasting technologies. Recognising the potential scalability issues as IPTV channels are being watched by a small fraction of viewers, the authors proposed the peer-to-peer content distribution paradigm as alternative, in particular for non-popular contents. The work targets bandwidth utilisation, video quality, and scalability issues and the findings show that multicast is more efficient, but peer-to-peer content delivery has a comparable performance for unpopular channels with a low number of viewers.

In [13], the allocation of cost (network utilisation) of a shared multicast tree was investigated in the context of multicast data flow. The work addresses a specific question of how a single multicast data flow is shared among receivers that subscribed to it. The work distinguishes between cost allocation and pricing. Pricing is the form and amount of payment received from end users while cost allocation is how the network assigns internally to itself, portions of the total cost to various users. The work concludes that the 'one-pass' accounting mechanism for allocating cost can be used to analyse both source-rooted and shared trees multicast protocols without modification since it only assumes that the route taken from a particular source to a particular receiver is independent of the group membership.

In [29], the authors studied the scaling behaviour of multicast techniques in different networks. They proposed some models for generating small-world Internet topologies. Simulation results showed that multicast tree size largely depends on network topology, and that if topology generators capture only the variability of vertex degree, then they are likely to underestimate the benefits of multicast technologies as tools for effective content delivery to large number of viewers.

The best quality of service (QoS) the Internet offers was reviewed in [30]. The authors proposed that residual uncertainty in QoS can be managed using pricing strategies. The framework was built on earlier work that was based on a nonlinear pricing scheme for cost recovery and then extends it to price risk. Though, a utility based option pricing approach was developed to account for the uncertainties in delivering loss guarantees, however, there were no simulation results that demonstrated their findings.

Hybrid contention-free/contention-based traffic management schemes in presence of delay-sensitive and delay-insensitive data in multi-hop CDMA wireless mesh networks was presented in [31]. Based on simulation results, the authors suggested a greedy incremental contention-based ordering algorithm for contention-free schedules and proposed a time-scale framework for integration of contention and contention-free traffic management.

In [12], the tradeoffs between PIM-SM and PIM-DM protocols were evaluated using two different performance metrics: (i) the state storage overhead metric and (ii) the control bandwidth overhead metric. The work ran simulations over the Arpanet topology with known group density (Density is defined as the percentage of on-tree link versus the number of links in the network). It concludes that for groups with densities less than 0.3 (A density value of 0.3 in the Arpanet corresponds to groups with 10% to 20% of the total number of network nodes) sparse mode operation has less storage and bandwidth overheads compared to dense mode. The work also concludes that the number of packets lost during transition from the rendezvous point (RP) tree (RPT) to shortest path tree (SPT) (i.e., black-out period) is a function of the path length difference between RPT and SPT branches and the source's inter-packet intervals (or the source's rate and packet sizes). The work found that high speed sources were more vulnerable to higher packets loss rates than low speed sources. It therefore advised that frequent switching from RPT to SPT should be done only if the gains worth it.

In PIM-SM, even if a receiver has switched to source rooted trees for all active sources, the router state still needs to be maintained for RP rooted tree to enable packets to be received from a new source of the group. Billhartz et al [14] studied the efficient way of managing state in PIM-SM by analysing and comparing PIM-SM with that of the core base tree (CBT) protocol. The work concludes that PIM-SM is a complex routing protocol given the size of the routing table and the impact of the timers on the operating system overhead for a large number of members that can potentially become sources. However, in spite of these findings, PIM-SM is probably the most widely deployed multicast protocol [15].

Charging multicast communication services has raised several challenging tasks like calculating the costs of distribution trees, multicast savings, and cost sharing mechanisms among receivers. In [16], a charging and accounting architecture, which supports multicast communications for IP Integrated Services (IntServ) [17] over asynchronous transfer mode (ATM) was studied. Another related work [18] suggests using network resource cost for pricing multicast communications. This work derives an approximation model for the cost of multicast trees with known group sizes. Different costing methods and cost sharing schemes are presented in [19], [20], [21], [22]. In [20], the locations of receivers and diameter of group members were taken into consideration in determining appropriate sharing schemes. Though our work is related to the papers we have reviewed, however we do believe to the best of our knowledge that there have been no analytical cost models for quantifying new and modified multicast protocols, in particular, PIM-DMSR and PIM-SSM protocols in non-strictly hierarchical networks.

3. Operational Features of the PIM Protocols

The cost of the protocols depends on how the protocols build and update their multicast distribution trees. PIM-SM [23] builds shared trees around one or more Rendezvous Points (RPs), (not necessarily the data source) from which data is multicast to group members. Potential receivers join the shared tree by sending an Internet Group Management Protocol (IGMP) join request to their local designated routers (DRs). The DR router (or node) merges the join request(s) of group members and sends a control message which is propagated along the shortest path tree to the RP node that is associated with a specific group. As the join message propagates toward the RP node, it instantiates forwarding state in intermediate routers to establish an RP rooted shared tree.

In PIM-SSM [9] the data source constructs and maintains group sessions by flooding the network with ‘channels’ *(U,G)* (where *U* is the source address and *G* the multicast address) using an IGMP control message. When the control message is received, routers would determine channels for which they have interested hosts. Subscriptions then travel hop-by-hop towards the data source router for the group and in each router a subscription passes through, multicast tree state for group *G* is instantiated.

PIM-DMFP [7] implements flood and prune mechanism to build and update its multicast group session. It assumes that when a data source starts sending multicast packets, downstream systems would want to receive multicast datagram. Therefore, at time t=0 the data source floods the entire network with a data packet and any router that has no interested hosts to receive data from the source will prune its interface out by sending a prune (control) message to upstream routers. This will cause the upstream routers to delete the interfaces of those downstream routers from the routing table. Therefore the data packets that arrive at routers which have no interested hosts (as a result of the flooding operation) are unwanted, and this increases the overhead of maintaining the distribution tree. Flooding and pruning is repeated every T_{FP} seconds.

PIM-DMSR [7] introduces a state refresh mechanism to maintain multicast groups. At t=0 (t measured in seconds), initial flooding of a data packet occurs and a corresponding pruning takes place. Thereafter, at every T_{SR} seconds a state refresh message is sent by the data source, which is propagated to all others nodes in the network. The refresh messages cause existing prune states of routers to stay pruned. The initial cost of a group is the same for both PIM-DMSR and PIM-DMFP protocols because of the initial flood and prune operation. The benefit of PIM-DMSR protocol is seen after t>0 (i.e., when control messages are used instead of data packets to update the delivery data path tree of a group).

4. Non-Strictly Hierarchical Network Architecture

In Fig. 1, we construct some logical links to connect the major ISP routers M_0, M_1, and M_2. In this network, router R_0 serves as both the root of the delivery data path tree and designated router (DR) for PIM-DM and PIM-SSM protocols. As PIM-DM protocol floods the network with a data packet, downstream routers with no interested members would prune themselves out of the group. As a result, M_1 router would receive 3 data packets through interfaces IF_6, IF_7, and IF_8 and would then determine which packet to forward by computing the shortest reverse path (SRP) to router R_0. The number of link from interface IF_6 to router R_0 is 3 links (i.e., M_1M_0, M_0Mn_0, and Mn_0R_0), from interface IF_7 to router R_0 is 4 links (i.e., M_1IP, IPM_0, M_0Mn_0, and Mn_0R_0), and from interface IF_8 to router R_0 is 5 links (i.e., M_1M_2, M_2IP, IPM_0, M_0Mn_0, and Mn_0R_0). If we assume that the bandwidth cost of every link is equal and is set to 1, router M_1 would accept the data packet received through interface IF_6 for forwarding, while the other data packets received through interfaces IF_7 and IF_8 would be dropped. The overhead cost of the dropped packets adds significantly to the total overhead costs of those protocols that employ flood and prune mechanism. Indeed, the control overheads can be very heavy in bigger networks.

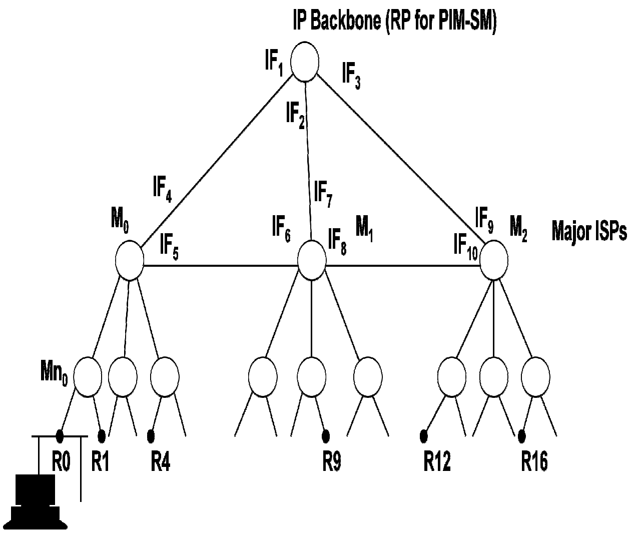

Figure 1. Non-strictly hierarchical network architecture. Note that R_0 serves as designated router (DR) and root of the data source, leaf routers R_1, R_4, R_9, R_{12} and R_{16} are active members of the group. **IF** refers to interface.

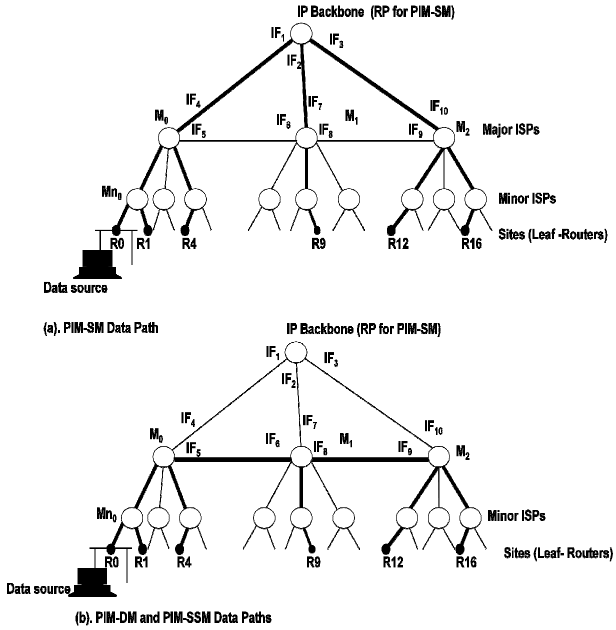

Figure 2. (a) The thick links show the distribution data path of the PIM-SM protocol, (b) the thick links show the data paths of the PIM-DM and PIM-SSM protocols.

5. Performance Cost Metric

We evaluate the cost behaviours of the protocols using control bandwidth overhead (CBO) incurred to maintain multicast groups in the network. In both sparse and dense modes operations in typical networks, the overhead varies more quickly than the actual data costs for different groups. Hence we choose to use CBO cost metric, assuming the links are symmetrical, in estimating the impact of the protocols in terms of the number of links traversed by a packet. Besides this, our choice of CBO cost metric may be appropriate in case of large networks where the group may be very large and hence the control costs, but data exchanges are small and relatively infrequent. Further motivations for the use of CBO are given in [25], [26].

If the size of a data packet is *D* and that of an IGMP control packet is *C*, and that node responses are not delayed and the maximum amount of merging possible actually takes place in branch routers and that groups are static, then this means that all round-trip times need to be less than the inter-packet arrival times, an assumption that is reasonable in the case of video of typical rates distributed with typical IP sizes of 500 - 1500 bytes, which is typically larger than a control message of at least 24 bytes [27]. It is possible to relax one or more of these assumptions.

6. Cost Model of Multicast Groups

In this section, we study the cost impact of the protocols when logical links are constructed to connect the major ISP branch routers at a level close to the IP backbone router. When the data source is outside the network, there is no significant change in the cost of the logical distribution trees of the protocols. However, when the data source is inside (or part) of the network as shown in Fig. 1, the logical links that connect the ISP branch routers decomposes the root of the delivery data path tree, thus the four level network becomes a mix of three level and four level networks as shown in Fig. 2. These changes can significantly affect the overhead costs of the different protocols.

The problem of quantifying the protocols in non-strictly hierarchical networks is similar to that of strictly hierarchical networks; except that the routers in the non-strictly hierarchical networks have one or more interfaces to receive datagram from the data source. Indeed, the more the number of interfaces a router has, the more overhead cost that is involved, especially for those protocols (e.g., PIM-DM and PIM-SSM) which employ flood and prune mechanisms to build and update their logical distribution trees.

We derive the cost model to measure the overheads of the protocols by decomposing the network in Fig. 1 into M_k (where k=0, 1, 2) three level networks such that the cost of a given multicast group is the weighted sum of each of the three level network cost plus the extra overhead of linking each three level network to the IP backbone router. In this respect, a given multicast group size, S can be restrictedly partitioned into M_0, M_1, and M_2 such that $\sum_{i=0}^{2} S_i = S$ (where S_i is the number of group members in i three level network) and none of the partitions in each of the three level networks exceeds its capacity. Let the extra overhead cost of linking i three level network to the IP backbone router be $e(S_i,\{s_i\})$. Then, the total overheads of linking the M_0, M_1, and M_2 networks to the IP backbone is thus $\sum_{i=0}^{2} e(S_i,\{s_i\})$.

Let the overhead cost of i three level network be $C(S_i,\{s_i\})$.

If M_0, M_1, and M_2 networks are assumed homogeneous, then $C(S_i,\{s_i\})$ is,

$$C(S_i,\{s_i\}) = \sum_{S_j=0}^{N_j} \sum_{s_1+\ldots+ns_i=S_j} \frac{(m_j)!}{s_0!\times s_1!\times\ldots\times s_n!} \prod_{j=0}^{n} \binom{n}{j}^{S_j} C(S_j,\{s_j\}) \quad (1)$$

Where N_j is the number of leaf routers in j three level network, m_j is the number of branch routers in j three level network, and $(m_j)!$ is the permutation of group members in j three level network. The sum of the overhead costs of M_0, M_1, and M_2 is $\sum_{i=0}^{2} C(S_i,\{s_i\})$.

The permutation of a given partition of a group in the M_0, M_1, and M_2 networks is

$$\sum_{S_0+S_1+S_2\in(0,1,2)} \frac{(S_0+S_1+S_2)!}{S_0!\times S_1!\times S_2!}.$$

Thus, the average overhead cost of the protocols assuming every group member is equally likely is,

$$\overline{AvCp} = \frac{\sum_{S=0}^{N} P(S) \sum_{S_0+S_1+\ldots+S_n\in\{0,1,\ldots,n\}} \frac{(S_0+S_1+\ldots+S_n)!}{S_0!\times S_1!\times\ldots\times S_n!} \left(\sum_{i=0}^{M} C(S_i,\{s_i\}) + \sum_{i=0}^{M} e(S_i,\{s_i\}) \right)}{\sum_{S=0}^{N} P(S) \sum_{S_0+S_1+\ldots+S_n\in(0,1,\ldots,n)} \frac{(S_0+S_1+\ldots+S_n)!}{S_0!\times S_1!\times\ldots\times S_n!}} \quad (2)$$

Where;

$\overline{AvCp}$ is the overhead of a given protocol averaged over the probability p,

N is the number of leaf routers (or stub-networks) at the lowest level of the network,

S is the size of a multicast group,

$P(S)$ is the Binomial distribution of multicast group of size S [24], which is defined as,

$$P(S) = p^S q^{N-S} \quad (3)$$

where p is the probability that a leaf router (i.e., a stub LAN) is a member of a group (and q is the probability that a leaf router is not a member of a group),

n is the number of leaf routers of a parent router,

$\{s_i\}$ is the restricted partition of S,

The multinomial coefficient computes the permutation of the restricted partition of a given multicast group of size S.

The Binomial model in (3) is the most simplistic assumption; however it gives equal weight for every group member, which might not be true in real world even though it prefers more spread out than less spread out groups. Different probabilities might help us to model the fact that different routers can have different numbers of end stations and hence have different probabilities of participation by group members. For example, a router located in the city of Lagos with large viewers' audience might have more traffic due to the number of end stations it serves, and hence has high probability of participation by group members attached to this router than a router located in rural Niger Delta State of Bayelsa with few end stations.

If, for example, a certain multicast group comprises R_0 (the root of the tree), R_1, R_4, R_9, R_{12}, and R_{16}, then the overhead cost of setting up this group by PIM-SM is,

$$C(S_i,\{s_i\}) + e(S_i,\{s_i\}) = 3D + 3C + 13C = 3D + 16C$$

3D+3C is the cost of registration incurred by router R_0, while the join cost is13C (see Fig. 1). The overhead of PIM-SSM is,

$$C(S_i,\{s_i\}) + e(S_i,\{s_i\}) = 32C + 13C = 45C$$

The cost of flooding the network with a control message packet is 32C, while the join overhead is 13C. The join overhead of routers R_9, R_{12}, and R_{16} is merged by router M_1, while the group overhead is then merged by router Mn_0. The overhead of PIM-DMFP and PIM-DMSR is,

$$C(S_i,\{s_i\}) + e(S_i,\{s_i\}) = 16D + 3D + 16C$$
$$= 19D + 16C$$

The flood cost is 16D + 3D (the extra overhead of 3D is incurred by links M_2IP, IPM_1, and IPM_0), the prune overhead is 16C. After the reverse path forwarding operation, which establishes the logical network (i.e., the distribution tree), the prune overhead of routers R_9, R_{12}, and R_{16} is merged by router M_1. The overhead of the group is finally merged by router Mn_0. The initial control cost of the group is equal for both PIM-DMFP and PIM-DMSR protocols since both protocols initially use a data packet to flood the network, expecting branch routers without downstream active member routers to prune themselves out of the distribution tree. After this initial process of establishing the distribution tree, PIM-DMSR then uses control message packet C to update (or refresh) its routers' states along the distribution tree while PIM-DMFP uses a data packet D for the same operation. This update process significantly differentiates the overheads of PIM-DMSR and PIM-MDFP protocols.

We generate numerical results from large networks using the combinatorial model in (1). The results are computed using C#. We validate our computed results against hand-calculated results by comparing the cost impacts of the protocols on small networks. We plot the average overhead per group member on the Y-axis against average fraction of routers for a given multicast group (*p*) on the X-axis. The results are presented in Fig. 3, Fig. 4, and Fig. 5 respectively.

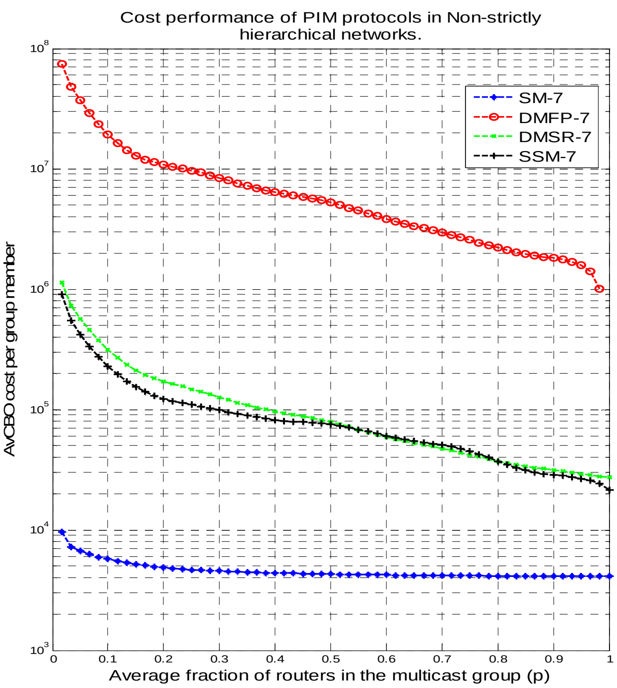

Fig. 3: Performance of the PIM protocols when major ISPs are connected.

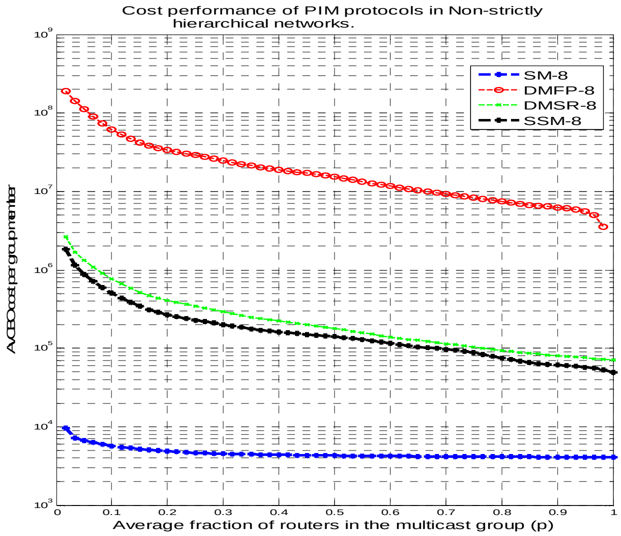

Fig. 4: Performance of the PIM protocols when minor ISPs are connected.

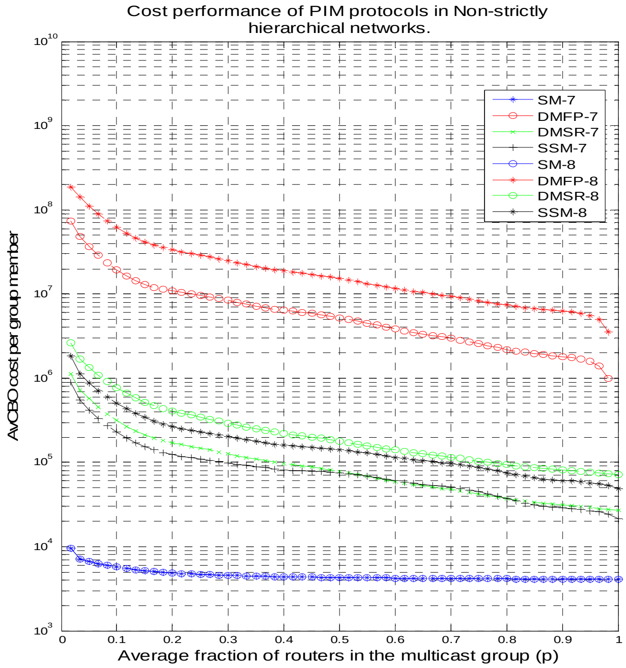

Fig. 5: Comparison of logical connectivity of major and minor ISPs.

Note**:** The specification of the network is N(6,2,5) (i.e., there are 6 routers connected to the IP backbone router, each of the 6 routers has 2 children routers, and each of the 2 children routers has 5 leaf routers. Therefore the number of leaf routers in the network is 60), data source is inside the network, both major ISPs (see Fig. 3) and minor ISPs (see Fig. 4) are logically connected on the assumption that the distribution of group members is Binomial. In Fig.5, graphs of major ISP connections are SM-7, DMFP-7, DMSR-7, and SSM-7, while minor ISPs are SM-8, DMFP-8, DMSR-8, and SSM-8.

7. Analysis of Results

We analyse the cost behaviours of the protocols by comparing the protocols from two perspectives - first when the major ISPs are logically connected and second, when the minor ISPs are connected on the assumption that the distribution of group members is Binomial. In both scenarios the overheads of the protocols per group member decrease as the mean group size increases (see Fig. 3 and Fig. 4). In the two scenarios, PIM-SM protocol is by far superior to the other three protocols since it exploits the advantage of the shared distribution tree. PIM-SSM protocol is seen to be slightly better than PIM-DMSR protocol (see Fig. 4) in particular, when minor ISPs are connected. PIM-SSM does slightly better than PIM-DMSR protocol because it uses only a control message to regenerate (or refresh) its delivery data path tree. Though the overhead of PIM-DMFP protocol drops faster than the other three protocols, however it relatively remains the worse protocol (see Fig.3 and Fig. 4)

Comparing the protocols on the basis of the two separate logical connections of major and minor ISPs, the overhead of PIM-SM protocol remains the same because it does not use flood mechanism like the other three protocols. Instead, it exploits the advantage of the core RP router, which serves as the shared delivery tree hence its overhead does not change (or increase) with respect to the number of logical connections as seen in PIM-SSM, PIM-DMSR, and PIM-DMFP protocols (see Fig. 5). All the protocols, except PIM-SM protocol refresh their distribution data paths by flooding the network hence they appear sensitive to the number of logical connections (or links) in the network. Though the results might be different where group membership (or connectivity) is based on the ratio of multicast traffic a router processes (or serves), however results from our simplified models provide some insights to what may happen in real-life situations.

8. Conclusion and Further Research Work

We have demonstrated the application of our combinatorial model in quantifying and analysing the overhead performance of the PIM variants in non-strictly hierarchical networks. Our results confirm that the PIM-SM protocol remains superior over the other three protocols in most mean group sizes. The work can help multicast protocol designers and network integrators to understand in general terms the properties of existing and newly proposed multicast protocols, in particular, how costs scale with network, group size, and data packet/control message. Our model can be used to determine and fine-tune flood, join/prune or state refresh intervals which are usually given as ad hoc defaults in Internet Engineering Task Force (IETF) documents.

One future research direction of our work is to model the overhead impacts of the protocols on the premise that the cost of a group is a function of the restricted partition of the group instead of the group size. This way, our model (1) can be generalised such that different upstream routers can have different probability of joining/leaving a group based on multicast traffic a router processes. Another future work would investigate how our numerical model (1) can be simulated in a real life research network using *ns2* (network simulation 2). Results from such study will reveal further details of how the protocols scale in different networks and hence, provide more and useful information in assessing the improvements of new, modified, and existing IP multicast protocols.

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