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Quantization of Sparse and Dense Mode Protocols in Ring Topology Networks

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***Abstract*: This paper provides analytical tools to assess the improvements of existing, modified or entirely new multicast protocols at an early stage of design. In particular, we investigate the general properties of sparse mode (SM) and dense mode (DM) protocols and their variants. Specifically, we quantify the performance of these protocols in a ring topology network using control bandwidth overhead (CBO) as cost metric. Our cost models are designed using combinatorial and restricted partitioning techniques. We compared our results with exhaustive enumeration technique and found that when p>0.4 (p is the probability that a router is part of a multicast group), DM with state refresh (DMSR) mechanism appeared relatively superior to SM and DM with flood and prune (DMFP) mechanism. Also studied is the precise measure of the relative performance between SM and source specific multicast (SSM) protocols.**

Keywords: Control bandwidth overhead, dense mode, ring topology networks, sparse mode, source specific multicast.

I. Introduction

In the early 1980s, Ethernet technologies for local area networks (LANs) supports multicast. The Ethernet defines a number of wiring and signalling standards for the physical layer, through means of network access at the Media Access Control (MAC)/Data Link Layer, and a common addressing format. It is standardised as IEEE 802.3 [1]. But extended LANs interconnected with bridges and inter-networks did not support multicast data delivery even though Internet Protocol (IP) version 4 (IPv4) [2] addressing scheme reserves Class D addresses for multicast from the beginning. During the same period [3], Steven Deering was motivated by his research work at Stanford University to think of the idea of implementing IP multicast in interconnected LANs as he was working on a network-distributed operating system called `Vsystem'. The system composed of several computers in a loosely coupled multiprocessing system via a single Ethernet segment. The computers on the Ethernet segment worked together and communicated at the operating system level via special messages sent on the common Ethernet segment.

At a point in his work, the need arose to add more computers to the multiprocessing system. Unfortunately, the only available computers were on the other side of the campus. Consequently, Deering had to extend the operating system's inter-processor communications to work at Network Layer of the Open Systems Interconnection (OSI) [4] reference model so that the computers on the other side of the campus could function as part of the loosely coupled multiprocessing system. Deering studied the Open Shortest Path First (OSPF) [5] Protocol and the Routing Information Protocol (RIP) [6] and consequently introduced multicast extensions to the unicast routing mechanisms across datagram-based inter-networks. The work eventually led to his doctorate paper on the subject (Multicast Routing in a Datagram Network) published in December, 1991 and subsequently, the premier IP-Multicasting Internet Engineering Task Force (IETF) document - Request For Comment (RFC) 1112 [7].

Following Deering's work, the Multicast Backbone (MBone) [8], [37] was born and marked the first widespread use of multicast in the Internet. The MBone is a collection of ‘islands’, where an island supports multicast within its domain. Each island has a host machine, which executes the *mrouted* multicast routing *daemon*. The *mrouted daemon* (in different islands) is connected to one another via point-to-point IP connections (called *tunnels*) over the Internet. In this way, the mrouted *daemons* and the *tunnels* that connect them form a virtual network on top of the Internet. The end points (workstations) of the MBone tunnels implement Distance Vector Multicast Routing Protocol (DVMRP) [9], [10] and are able to process unicast-encapsulated multicast packets and then forward the packets to the appropriate outgoing interfaces computed by the routing protocol. In March 1992 [8], the MBone carried out its first event with 20 sites, and multicast audio streams were received from a meeting of the Internet Engineering Task Force (IETF) in San Diego.

In the last few years, the need to deploy IP multicast services at reasonable benefits (e.g. bandwidth savings) [24], [9] has gained increasing popularity among multicast protocol designers and network integrators. This led to an increase in the number of publications in the literature [39] and several multicast protocols emerged. Some of these multicast protocols include DVMRP [11], Multicast Extensions for OSPF [12], Core Based Tree (CBT) [13], Protocol Independent Multicast (PIM) [14], [15], [16], Explicitly Requested Single Source (EXPRESS) [17], Simple Multicast [18], Multicast Internet Protocol (MIP) [19], etc. Also emerged recently from research work are PIM-dense mode with state refresh (PIM-DMSR) [23], PIM-dense mode with flood and prune (PIM-DMFP) [23] and PIM-source specific multicast (PIM-SSM) [20], [21], [22]. Though, these developments have enhanced group communications over the Internet, however, we do believe to the best of our knowledge that there have been no analytical tools to assess the improvements of these modified and new multicast protocols, in particular, PIM-DMSR, PIM-SSM, PIM-DMFP, and PIM-SM protocols in a ring topology network. We are therefore motivated to do this research work with a view to studying the general properties of these protocols and designing tools to quantify their performance in a ring topology network (work on strictly hierarchical and non-strictly hierarchical network topologies have been investigated elsewhere).

The rest of this paper is organised as follows. We review related work in section II while section III discusses the operational mechanisms of the PIM protocols. Section IV presents the network architectures while section V specifies the performance metric use in evaluating the PIM protocols. Section VI presents our cost models. We discuss our results in section VII while section VIII concludes the paper and states future research direction.

II. Related Work

There has been a growing literature on implementation/deployment of multicast technologies in different network platforms. Y. Peng et al [25] analysed multicast capability in a multicast-capable optical add/drop multiplexer (MC-OADM) and investigated the dynamic network performance of the MC-OADM ring in comparison with the normal OADM ring without multicast capability. The simulation results show that the MC-OADM scheme provides more multicast services with fewer resources than OADM scheme.

X. Wang et al [45] investigated the scaling law for multicast traffic with hierarchical cooperation [48], where each of the n nodes communicates with k randomly chosen destination nodes. By utilising the hierarchical cooperative MIMO transmission, their scheme obtained an aggregate throughput of $\Omega((\frac{n}{k})^{1-\epsilon})$ for any $\epsilon > 0$. This achieves a gain of nearly $\sqrt{n/k}$ compared with the non-cooperative scheme in [46].

K. Dimitrios et al [44] presented the hierarchical geographic multicast routing (HGMR) protocol, which incorporates the key design features of geographic multicast routing (GMR) protocol to optimise both forwarding capability and scalability to large networks. Simulation results show that, in ideal environment, HGMR incurs a number of transmissions either very close or lower than GMR. Also, HGMR has lower packet delivery latency than GMR, as well as, more efficient with uniform and non-uniform group member distribution.

F. Zhou et al [47] reviewed their light-tree scheme and proposed a light-hierarchy structure, which accepts cycles that are used to traverse crosswise a 4-degree multicast incapable (MI) node twice and switch two light signals on the same wavelength to two destinations in the same multicast session. By extending the Graph Renewal and Distance Priority Light-tree algorithm (GRDP-LT) to compute light-hierarchies, obtained numerical results demonstrate that the GRDP-LT light-tree can achieve a much lower links stress, better wavelength channel cost, smaller average end-to-end delay, and diameter than the currently most efficient algorithm.

In [26], the fairness between unicasting and multicasting was investigated in slotted packet-switched WDM ring networks that employ a tuneable transmitter and fixed tuned receiver at each node and a posteriori buffer selection. The work finds that the single-step longest-queue (LQ) buffer selection results in unfairness between unicasting and multicasting. In the light of this, the authors proposed and evaluated dual-step buffer selection policies that achieve and allow for a range of relative priorities of multicast versus unicast.

A. Bikfalvi et al [27] reviewed the Internet Protocol TV (IPTV) services which is a preferred alternative to broadcasting technologies. Because of its potential scalability issues as IPTV channels are 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.

A. Neishaboori et al [28] investigated hybrid contention-free/contention-based traffic management schemes in presence of delay-sensitive and delay-insensitive data in multi-hop CDMA wireless mesh networks. Based on simulation results, the authors suggest 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.

M. Scheutzow et al [29] developed an analytical methodology for calculating the transmission, reception, and multicast capacities of unidirectional and bidirectional packet-switched ring WDM networks. For different unicast, multicast, and broadcast traffic scenarios, the authors numerically examined the impact of the number of ring nodes and the fan-out of multicast packets on the capacity performance of both ring networks. The findings are that, for broadcast traffic and for large multicast fan-out, the packet forwarding burden on the ring nodes is high, resulting in a decreased transmission capacity. For an increasing number of nodes, spatial wavelength reuse diminishes and the transmission capacity of both unidirectional and bidirectional ring networks asymptotically drops down to the number of wavelength channels. This means that for broadcast and multicast traffics with large fan-out, the capacity improvement is due to spatial wavelength reuse for increasing number of ring nodes.

Spatial wavelength reuse or destination stripping increases the capacity of packet-switched unidirectional and bidirectional ring networks and promotes them to support multicast traffic. Chaitou et al [30] developed an analytical model to evaluate the maximum achievable transmitter throughput of such networks in presence of multicast traffic. The mean access delay of a multicast packet was investigated using the discrete Geom/Geom/1 queue system and on the computation of blocking probabilities. The results are validated by simulations and the impact of self-similar traffic shown. The work provides a simple analytical tool for comparing the impact of multicast on access delays and multicast capacity in future slotted ring networks. An analytical investigation of the mean hop distance of shortest routing bidirectional optical WDM ring networks for multicast (with arbitrary fan-out), unicast, and broadcast traffics are presented in [31]. Different costing methods and cost sharing schemes are presented in [32] and [33]. Though our work is related to these papers we have reviewed, however we do believe to the best of our knowledge that there have been no analytical tools to assess the improvements of new and modified multicast protocols, in particular, PIM-DMSR and PIM-SSM protocols in ring topology networks.

III. Operational Mechanisms of Protocol Independent Multicast (PIM)

A. Protocol Independent Multicast-Sparse Mode (PIM-SM)

PIM-SM 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 the 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. A data source constructs a unicast shortest path tree to the RP node before sending data over the shared tree (see Figure 1).

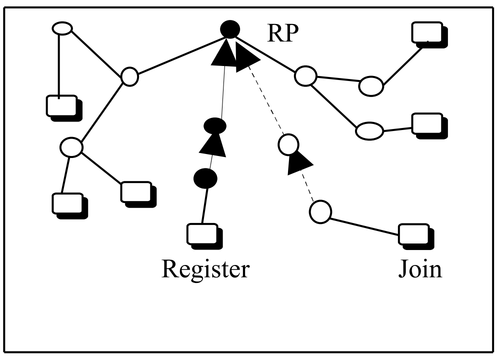

Figure 1. Register and join procedures in PIM-SM

B. Protocol Independent Multicast-Source Specific Multicast (PIM-SSM)

PIM-SSM is a datagram delivery model of Cisco implementation of IP multicast solutions, which is targeted at audio and video broadcast applications. It provides support for one-to-many delivery only. It is a model in which the only packets that are delivered to a receiver are those originating from a specific source address requested by the receiver. PIM-SSM is best understood in contrast to any-source multicast (ASM) [34]. In ASM service model a receiver expresses interest in traffic from any multicast address whereas in the PIM-SSM model, a receiver expresses interest in traffic from only one specific source that sends data to the multicast address. By limiting the source, PIM-SSM relieves the network of discovering too many multicast sources and by this; it does not only reduce the amount of multicast routing information that the network must maintain, but also improves security in the network. The specification of the source address by a receiver is however possible only in IGMPv3 [35], [36] of IPv4 and multicast listener discovery version 2 (MLDv2) [35] of IP version 6 (IPv6) [35]. To construct and maintain group sessions, a data source floods the network with 'channels' *(U,G)* (where *U* is the source address and *G* the multicast address) using 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.

C. Protocol Independent Multicast-Dense Mode (PIM-DM)

PIM-DM protocol is of two versions, PIM-DMFP and PIM-DMSR protocols. PIM-DMFP implements flood and prune mechanism (see Figure 2) to create and update 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 as a result of the flooding operation are unwanted. Flooding and pruning is repeated every T_{FP} seconds.

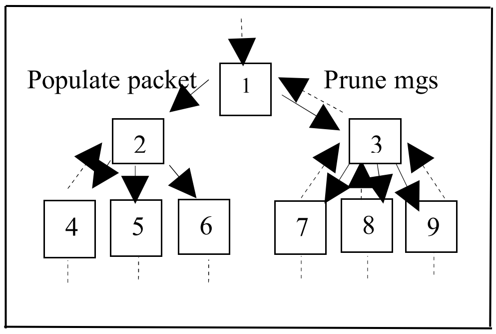

Figure 2. Generation of prune message and distribution to parent routers.

In Figure 2, a prune message is generated and sent to a parent router. Nodes 7, 8, and 9 sent a prune message respectively to parent router 3, which aggregates all prune messages and sent a copy to the parent router 1. Node 2 does not generate a prune message because it only received a prune copy from node 4. This means that any multicast packet that arrived at node 2 would be sent to nodes 5 and 6.

IV. Network Architecture

We study the cost behaviours of the protocols in a critical mission ring topology networks as shown Figure 3. We focus our study on the critical ring networks, which is a ring-like topology. That is, our work does not include the cost of linking edge networks that serve local internet service providers (ISPs) and third party networks in the analysis. After reverse the path forwarding (RPF) operation [43], the physical ring network decomposes into a logical network with two branches of which, the router B2 serves as the RP interface between the left branch and the right branch of the network as shown in Figure 4. This decomposed logical network has features similar to that of hierarchical networks [40]; hence we address the cost behaviours of the protocols using combinatorial and restricted partitioning techniques [41], [42] to model the overheads of the protocols in the ring networks.

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 motivation for the use of CBO as cost metric is given in [40].

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 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 [39]. It is possible to relax one or more of these assumptions.

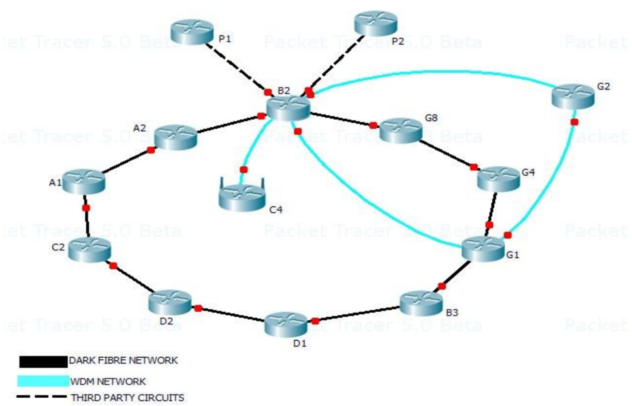

Figure 3. A ring topology with dark fibre network (i.e., critical network), WDN networks, and third party networks.

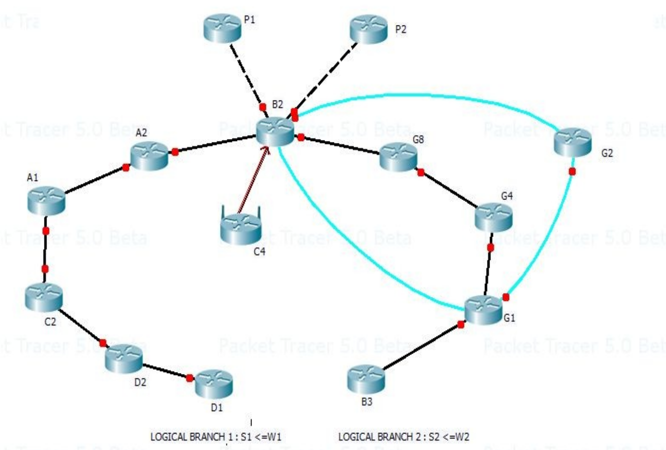

Figure 4. A decomposed ring network tith two branches after RPF operation.

In Figure 4, the RP (i.e. node B2) router serves as the interface between the left branch and the right branch of the logical network. The data source is C4 router.

V. Performance Cost Metric

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VI. Cost Model

Let W be the number of nodes in the ring network; then W can be divided into $W1$ (the number of nodes in the first branch of the logical network) and $W2$ (the number of nodes in the second branch of the logical network). Then a group of size S can be restrictedly partitioned such that $s1 + s2 = S$ (where $S1$ is the number of group members in the first branch, while $S2$ denotes the number of group members in the second branch of the logical network), $s1 \leq W1$ and $s2 \leq W2$. Let the cost of a group be a function of the location of the deepest member router. That is, the deepest member router is the farthest location of a member router from the IP router (the IP router serves as interface between W_1 and W_2). If there are W_1 fixed routers in the first branch then there are W_1+1 different costs, each corresponding to the location of the deepest router in the branch.

If the number of nodes in a certain ring network is 5, (i.e., $N=5$), $W_1+W_2=2$, the IP backbone router serves as interface between the two branches of W_1 and W_2, and $S=1$; then if a group member is located in the router next to the IP router, the overhead cost of PIM-SM protocol is C as only one link is traversed by a control message packet. However, if a group member is located in the bottom router, which is the deepest location from the IP router in this example, it will cost PIM-SM protocol $2C$ as two links are traversed by a control message packet. Following this argument, when a group member is located in a router next to the IP router, it costs the PIM-DM protocol $D+C$ as the bottom router would send a prune message to the upstream router as it has no interested member in its sub-network. When the only group member is located in the bottom router of the branch, the overhead cost of PIM-DM protocol is 0 as no prune cost is incurred. It therefore follows that the overhead cost of a group is a function of the location of the farthest (or deepest) member router from the IP router.

Let $C(i)$ be the cost of a certain group when one of the group members is located at depth i router from the IP interface router, then we want the probability of this group conditioned on the number of routers in a branch. For example, if there are no group members (i.e., $S=0$) in a branch, then the probability of $p(0)=1$. If there is one group member (i.e., $S=1$) in a branch, then the probability of $p(0)=0$, while the probability of every other group is $\frac{1}{W_1}$. Therefore, in general the probability of each group is,

$$p(0)=0$$
$$p(1)=\frac{1}{W_1}$$
$$p(2)=\frac{1}{W_1}$$
$$\vdots$$
$$p(i)=\frac{1}{W_1}, 1\le i\le W_1$$

Another example is that, if a branch has two group members (i.e., $S=2$) and there are 5 fixed routers in the branch, then the probabilities of all the groups given that the two routers which are randomly and independently chosen include the farthest member router from the IP router is computed as follows. Let the fixed routers in the branch be labelled 1,2,3,4, and 5. Then the number of groups that can be randomly and independently generated are 10 (i.e., (1,2), (1,3), (1,4), (1,5), (2,4), (2,5), (3,4), (3,5), and (4,5)). The probability of each group is generated thus,

$$p(0)=0$$
$$p(1)=0$$
$$p(2)=\frac{(1,2)}{10}=\frac{1}{10}$$
$$p(3)=\frac{(1,3)+(2,3)}{10}=\frac{2}{10}=\frac{1}{5}$$
$$p(4)=\frac{(1,4)+(2,4)+(2,4)+(3+4)}{10}=\frac{3}{10}$$
$$p(5)=\frac{(1,5)+(2,5)+(3,5)+(4,5)}{10}=\frac{4}{10}=\frac{2}{5}$$

i.e., $\sum p(i)=1, 2\le i\le 5$.

Furthermore, if $S_1=3$ and $W_1=6$, then the number of multicast groups that are generated from the network is 20 (i.e., (1,2,3), (1,2,4), (1,2,5), (1,2,6), (1,3,4), (1,3,5), (1,3,6), (1,4,5), (1,4,6), (1,5,6), (2,3,4), (2,3,5), (2,3,6), (2,4,5), (2,4,6), (2,5,6), (3,4,5), (3,4,6), (3,5,6), and (4,5,6)). The probability of each group is,

$$p(0)=0$$
$$p(1)=0$$
$$p(2)=0$$
$$p(3)=\frac{1}{2}$$
$$p(4)=\frac{3}{20}$$
$$p(5)=\frac{3}{10}$$
$$p(6)=\frac{1}{2}$$

i.e., $\sum p(i)=1, 3\le i\le 6$

Therefore, in general the probability of a certain group is thus,

$$p(i)=\frac{1}{Wi} \tag{1}$$

The permutation of $S1$ routers in the available locations of $W1$ fixed routers in the first branch is $\binom{W1}{S1}$. Similarly, it is $\binom{W2}{S2}$ in the second branch of $W2$ fixed routers. Therefore, the permutation of the restricted partition of a group of size S, denoted by Q is thus,

$$Q=\sum_{S1+S2=S}\sum_{i=1}^{2}\binom{W_i}{S_i} \tag{2}$$

That is, we are summing over all the partitions of *S* to obtain the number of multicast groups that are generated from a given group of size *S*.

If we assume that a member of a group has probability *p* (and *q* is the probability that a router is not a member of a group), then *P(S)* is a Binomial distribution,

$$P(S)=p^S q^{W-S} \tag{3}$$

Thus, the weighted average overhead cost of the protocols in the ring topology network is computed by summing over the probability p as,

$$\overline{AvCBOp} = \frac{\sum_{S=0}^{W} P(S)QC(i)}{\sum_{S=0}^{W} P(S)Q} \quad (4)$$

By setting $W = 31$ nodes, $W_1 = W_2 = 15$ nodes, the middle router designated to control the two branches, we generate numerical results from cost model (4) using C#. The results show how the overhead costs of the protocols vary relatively in the ring topology network (see Figure 5).

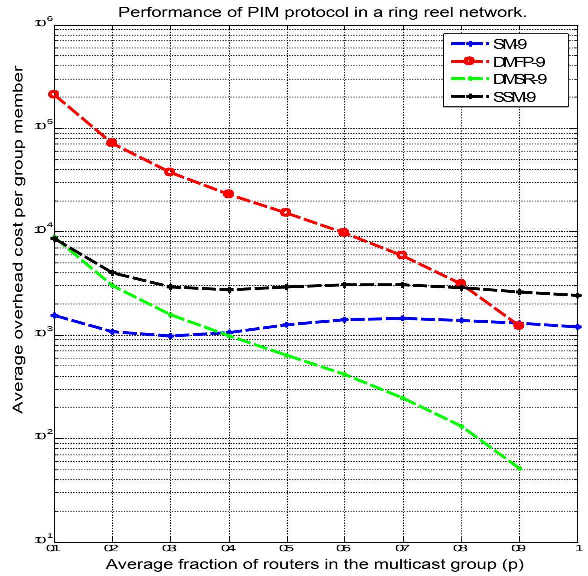

Figure 5. Performance of the PIM protocols in ring topology networks.

Note: SM-9, DMFP-9, DMSR-9, and SSM-9 are graphs of PIM-SM, PIM-DMFP, PIM-DMSR, and PIM-SSM respectively.

VII. Analysis of Results

As shown in Figure 5, all the protocols exhibit similar cost trends, i.e., they all narrow down as the mean group increases. However, PIM-DMSR protocol does better than the other three protocols when p>0.4 (i.e., when the number of group in the network is greater than 12). This happens because as the number of group increases, it is likely that downstream member routers in the logical network would not send prune messages hence the overhead of PIM-DMSR decrease as the mean group increases. Though, the same situation applies to PIM-DMFP protocol, however a prune operation of PIM-DMFP protocol involves a data packet, which is quite larger than a control message hence PIM-DMFP protocol utilises more bandwidth and relatively poorer than PIM-DMSR protocol.

PIM-SM protocol does better than PIM-SSM protocol because for every multicast group formation PIM-SSM protocol operation involves flood and join operations using a control message packet, whereas the formation PIM-SM group does not require flood operation, rather members use control message packet to join any group of which they have interest. Also, because the IP router serves as the interface between the two branches of the logical network, PIM-SM operation does not involve cost of registration hence its overhead is consistently better than PIM-SSM protocol.

As shown in Figure 5, PIM-DMFP protocol remains the poorest protocol, except for very large groups which do not involve control cost. The poor performance of PIM-DMFP protocol is that it uses a data packet to refresh and update its multicast distribution tree.

In general, in the ring network, PIM-DMSR protocol relatively utilises less bandwidth for large groups hence it is more cost-effective at that scenario than the other three protocols. While for small group, PIM-SM protocol proves superior over the other protocols - the results corroborate the work on hierarchical topology networks [38].

VIII. Conclusion and Future Work

We have developed analytical models for calculating and quantifying the control costs of the PIM protocols in ring network of average sizes. Our models are designed using combinatorial and restricted partitioning techniques.

We generate multicast groups and their probabilities on the assumption that group membership depends on the location of the deepest router (or farthest) member router of the group to the IP backbone router. This enables us to compute both probabilities and costs of the groups, which vary in relation to the assumption. We validated our results in a small network. However, for very large networks with several nodes, it can be cumbersome to accurately generate the probabilities of all multicast groups.

For the different PIM variants, we have numerically examined their operational impacts in the ring topology networks. Results confirm that PIM-DMSR protocol is better than the other protocols for large groups, while for small groups, PIM-SM protocol proves superior over the other three variants. Therefore, if certain amount of bandwidth is allocated for maintaining these protocols, then this analysis can very useful, in particular to multicast designers, network integrators, and network administrators.

Our future research work would investigate how our analytical model (3) can be simulated in a real life research network using *ns2* (network simulation 2). This would enable us compare our analytical results with real-life performance of these protocols and hence, provide more and useful information that could help to fine-tune the refresh and update frequency of these PIM protocols.

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