New Approach to Inter-domain Multicast Protocols

Raquel Pérez Leal, Juan Ángel Cachinero, and Encarna Pastor Martín

IPTV broadcast channels and video content distribution are increasingly saturating network paths. New solutions based on inter-domain multicast protocols could contribute to the enhancement of multimedia content distribution over the Internet. The aim of this paper is to propose new capabilities for an existing inter-domain multicast protocol, the Protocol Independent Multicast-Sparse Mode. We describe the modified protocol and analyze its behavior using newly developed tools based on an open-source software simulator. The resulting protocol does not require topology information, which is advantageous for easier deployment. In addition, the adopted solution avoids inherent problems with inter-domain multicast routing, such as multiple paths and path asymmetries.

Keywords: Inter-domain multicast routing, PIM-SM, IPTV, multicast protocol, simulation, broadcast.

I. Introduction

Internet real-time content services, such as IPTV broadcast service and multimedia content distribution, are technically limited in terms of network growth, efficiency, and requirements regarding bandwidth, delay, and scalability. Content distribution is dominated by peer-to-peer and content-distribution-network technologies, [1], [2], which are adequate for uses in different environments. However, the large increase in traffic and demand in peer-to-peer technologies and the investment required in content distribution networks require either new solutions that combine features from both areas or the introduction of new architectural network aspects. We believe that further research on network multicast-based solutions could enhance multimedia content distribution.

Given the multidomain nature of the Internet, multicast functionality across multiple autonomous systems is necessary. Inter-domain networks consist of multiple autonomous systems that are operated by multiple service providers and infrastructure operators. Consequently, different domains usually have different management policies as well as agreements to route traffic from other provider domains; in addition, they have various routing mechanisms, and they lack knowledge regarding the topological detail of areas administered by others. This complexity has been one of the main barriers to the wider use of IP multicasting on the Internet.

Nevertheless, there is broad consensus on the potential of multicasting for greater efficiency of content distribution. Inter-domain multicasting could drastically improve network efficiency for real-time and continuous media distribution services, including IPTV, multiparty video conferencing, and data broadcast to multiple users.

The aim of this paper is to propose new capabilities for an existing inter-domain multicast protocol, that is, the Protocol Independent Multicast-Sparse Mode (PIM-SM) [3]. In the

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modified protocol, topology information is not required, which is advantageous for easier deployment. In addition, problems inherent to inter-domain multicast, such as multiple paths and path asymmetries, are avoided. As a part of this study, we defined several scenarios and ran extensive simulations using OMNeT++ to carry out a comparative analysis among standard and modified PIM-SM protocols in term of quality of service levels.

A brief overview of IP multicast is presented here with a focus on inter-domain multicast. Then, we analyze existing proposals for inter-domain multicast protocols. We focus on PIM-SM and describe its characteristics and the problems arising from the inter-domain aspects in section III, which is followed by a discussion regarding modifications to the standard protocol in section IV. We present the simulations carried out to validate our approach in section V. Finally, a thorough analysis of our results and conclusions are presented in sections VI and VII, respectively.

II. IP Inter-domain Multicast

1. Overview

IP multicast allows for the simultaneous transmission of a single data traffic flow from a single source to multiple receivers. This concept was introduced by Deering in 1989 [4], and later expanded by the same author in 1990 [5]. It is implemented at the network level, allowing for better performance benefits and application simplification compared to overlay multicast solutions [6], although routers must incorporate additional functionality.

Currently, multicast techniques are deployed on operator networks, such as in the delivery of linear IPTV channels. The main advantage of network multicast is the overall bandwidth reduction as compared with unicast transmission requirements.

The main processes involved in a multicast system are tree building and routing and group management. At present, several network IP multicast protocols have been standardized, and some proprietary protocols have also been proposed to carry out the routing process. The PIM-SM, PIM-Dense Mode (PIM-DM), PIM Bidirectional, Distance Vector Multicast Routing Protocol (DVMRP), Multicast Extension to Open Shortest Path First (MOSPF), and Border Gateway Multicast Protocol (BGMP) are standardized protocols that were analyzed in [7]. This reference provides a good review of multicast Internet routing architecture and information on the implementation of these protocols.

However, other protocols are required to support multicast. For example, the Internet Group Management Protocol (IGMP) [8] and Multicast Listener Discover (MLD) [9] are used for membership establishment, whereas joint and leave functionality and the Multicast Source Discovery Protocol (MSDP) [10] collect information about active sources. All of these support protocols are beyond the scope of this paper.

Inter-domain multicast networks require support from routers, both intra-domain and at domain borders, a greater ability to maintain proper control of traffic and congestion, and state tables with identifiers of the multicast groups including different domains.

In general, the relevant limitations for the deployment of inter-domain multicast include:

- Domain reach. Selective inter-domain network prefixes exportation may generate walls between different areas of the whole network.
- Asymmetric routes to connect two final nodes located in different domains. Two fixed nodes in different domains may have disjointed routes to connect them at the inter-domain level.
- Multiple paths. Together with asymmetric routes, there may be multiple paths between any two nodes from different domains.

2. Related Work

While IP multicast routing improves network efficiency, it poses problems for universal deployment, especially when an inter-domain is involved. IETF in [7] summarizes the applicability of multicast protocols to the inter-domain field. PIM-SM is the best and most widely implemented candidate [3]. With regard to proprietary protocols, [6] also analyzes the Next Branch Multicast (NBM) [11], Global Multicast Routing Protocol (GMRP) [12], Domain Constrained Multicast (DCM) [13], and Policy Aware QoS Inter-domain Multicast Routing (PAQoSIDMR) [14] in terms of video broadcast support and inter-domains. The NBM and DCM seem to be adequate to support video multicast, and PAQoSIDMR builds multicast trees to account for QoS requirements. Nevertheless, neither the NBM, DCM, nor PAQoSIDMR have been deployed yet for these purposes.

Inter-domain routing raises several important issues related to topology, and the PIM-SM is not exempt from these problems. The more significant issues are route asymmetries, route isolation, and route convergence, as a group member can be reached by multiple paths simultaneously. Some solutions have been proposed to solve these problems; these solutions are mainly based on proprietary protocols. Note that [15] proposes hop-by-hop (HBH) multicast routing as a solution to provide multicast service supported by unicast clouds with transparency. HBH addresses asymmetry problems by constructing shortest-path trees (SPTs) instead of the reverse path forwarding (RPF) used in the PIM-SM to provide the best routes in asymmetric networks. The NBM [11] uses a similar approach based on branching nodes, unicast support, and SPTs. Moreover, it eliminates some inefficiencies existing in the previous solutions. The HBH and NBM use the unicast address scheme to simplify deployment; however, this method is more complex and requires additional resource requirements at the router level. In fact, neither the HBH nor NBM take advantage of the IP multicast address scheme.

Among the analyzed proprietary solutions, some protocols confine the multicast distribution trees within each network domain, which coincide roughly with autonomous Internet systems. Their primary purpose is to facilitate universal multicast deployment and to take advantage of the existing multicast IP island in a network. Focusing on the PIM-SM, these approaches can also avoid the route asymmetries, isolation, and convergence problems that appear when support protocols and multicast topology information such as the Multicast Routing Information Base (MRIB) are not used. In [16] and [17], two interesting examples of multicast traffic confinement in islands are provided. As presented in [16], the so-called Universal Multicast (UM) framework uses native IP multicast where available and unicast tunnels to connect islands. In this context, an overlay multicast protocol (HMTP) for inter-island routing and an intra-island multicast management protocol (HGMP) are defined. In addition, this framework requires a daemon program at the host level.

In [17], referring to an earlier version [16] from 2002, Cheuk proposes the Island Multicast (IM), which combines IP multicast with application-level multicast. The paper details the mechanisms for electing the bridging nodes and the leaders in an overlay application for overlay connections.

Based on the multicast tree confinement principle, the DCM [13] employs modified IPv6 multicast addresses. In the DCM, all of the inter-domain border routers run the protocol entities. Applying a similar principle in the case of PIM-SM multicast inter-domain routing, the distribution of multicast trees can be confined within each domain and thus use tunnels between domains. This approach does not require modified multicast addresses, which is an advantage over the DCM, and it does not require additional application support as is the case in [16] and [17].

We propose to incorporate new inter-domain mechanisms to PIM-SM for multicast traffic confinement based on existing protocol elements, such as RP and PIM modified messages.

III. Discussion of PIM-SM Protocol

Among the different multicast routing protocols, the present paper focuses on the PIM-SM [3] because of its deployment level and potential support of video broadcast services [11].

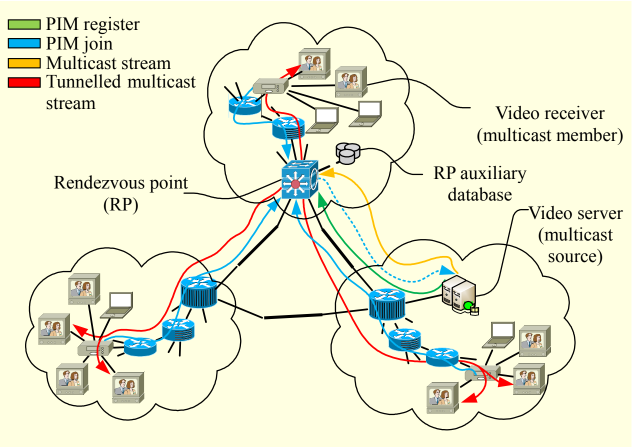

Fig. 1. PIM-SM inter-domain multicast topology.

The PIM-SM, which is standardized by the IETF, is designed to operate in scenarios with a small number of multicast users relative to the total hosts connected in the network.

The PIM-SM is able to build distribution trees and to deliver content in small and large networks on inter-domain environments. It runs based on a unicast routing information base (RIB) instead of a multicast topology database (MRIB). This feature is advantageous because it makes the system independent from the underlying protocol.

The PIM-SM protocol distribution and control are centralized in a rendezvous point (RP). This element, along with other aspects of the model, is presented in Fig. 1.

The first step in the PIM-SM process is source association. The sources request registration at the RP by a so-called PIM-register message. The next step is the subscription of the members to one group. To accomplish that, a member sends a join request through the intermediate routers and the routers resend it to the RP using PIM-join control messages. PIM-join messages also play a role in creating multicast inputs associated with the concerned group at the router interfaces by the algorithm RPF. RPF is supported by unicast RIB to find the path to the RP (that is, from members to RP), thereby generating a reverse distribution tree from the RP to members.

At this point, the RP extracts the content flow from the tunnel provided by the video source and starts the multicast distribution through the shared tree.

Once the shared trees are established, the PIM-SM can switch to the specific tree approach. In fact, there is an option to connect directly to sources and multicast members without RP mediation, thus avoiding the need for tunnel building. This connection is performed in the Source-Specific Multicast Operation Mode (PIM-SSM), and it may be performed even when several PIM domains are implied [18].

The use of a routing multicast protocol like PIM-SM has a number of advantages, especially the support for specific source-based and shared trees, the independency of the underlying routing protocol, and the capacity for operation at both the intra-domain and inter-domain levels.

However, the main drawbacks of the PIM-SM are that the message formats are different between the various PIM protocol modes. In addition, there is a risk of saturation of PIM-SM routing state tables when the number of sources is very high and specific source trees are used. Finally, admission control, join, pruning, and other control aspects should be implemented at both the intra-domain and inter-domain levels.

After weighing the advantages and disadvantages, the PIM-SM is still the preferred option for further analysis and simulation and thus serves as the starting point for proposals for improvements to video broadcast service support on inter-domain networks. The next section discusses these topics in greater detail.

IV. PIM-SM Modification Proposal

We propose two modifications to the standard model of the PIM-SM to allow full implementation in an inter-domain scenario while using support protocols, MRIBs, and detailed topological information as little as possible. These features are advantageous in maintaining the independence of PIM-SM from underlying routing protocols.

1. PIM-SM-Direct Path Forwarding (PIM-SM-DPF)

The existence of asymmetric routes with disjoint paths connecting any two nodes occurs in inter-domain network scenarios. This context implies improper PIM-SM operation in the absence of support protocols. The construction of PIM-SM multicast trees is based on the RPF algorithm. This algorithm creates entries on the router interfaces located in the opposite direction to the movement of PIM-join messages to create a direct path, as can be seen from the opposite side at the root of the tree. Therefore, multicast packets can be delivered to multicast members. However, if the paths connecting two nodes on the network are asymmetric, the routes connecting them are disjointed. If there is no auxiliary MRIB information for the correct calculation of direct and reverse routes, the RPF algorithm will fail because the reverse path routes do not match the branches created by the PIM-join messages. In addition, certain transit domains export their prefixes only to some domains connected to them directly or indirectly. If a backbone router in a transit domain receives packets from a domain to which the backbone router has not exported its prefixes, the router will discard the packets. This situation creates barriers depending on the direction followed by the packets, causing the RFP to fail in the absence of support protocols. Figure 2 shows the problem related to the asymmetric routes. Multicast packets cannot follow the reverse route created by the RPF, that is, the routers traversed by the blue arrow, and so they must go through another domain and are discarded.

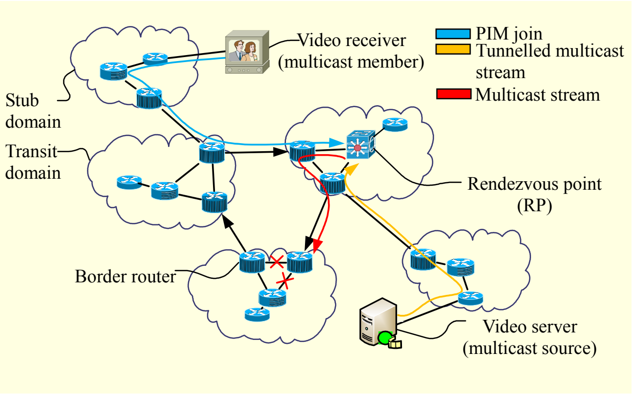

Fig. 2. Inter-domain path asymmetries.

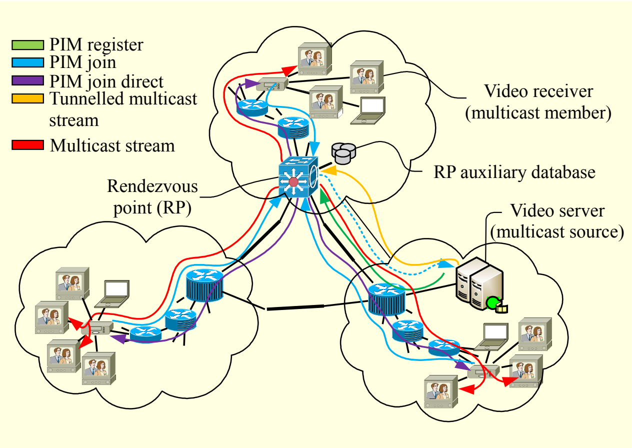

Fig. 3. PIM-SM-DPF proposal.

To allow operation without the use of support protocols and auxiliary databases, we modified the original model of the PIM-SM protocol. The Direct Path Forwarding modification proposal (PIM-SM-DPF) consists of changing the operation of tree building and replacing the RPF algorithm with the DPF algorithm. PIM-join messages do not create entries in PIM routers in their path to the RP. Instead, when a PIM-join arrives at the RP, it is analyzed, and a new PIM message is created. This so-called PIM-join_Direct message is sent from the RP towards the member that initiated the process. The new packet goes through the network and creates entries in PIM routes, though in outgoing network interfaces. Therefore, a multicast tree is built in direct RP-to-member paths. The created branches are fully circulated and reach out to all group members.

The functional model of PIM-SM-DPF is shown in Fig. 3. The main difference from the original PIM-SM model is the

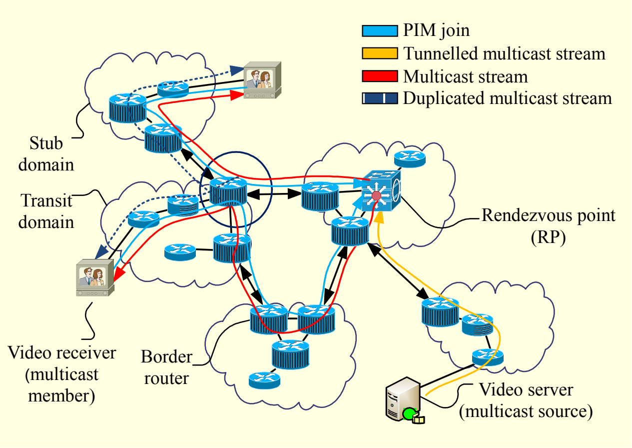

Fig. 4. Multicast tree branch convergence.

presence of new PIM-join_Direct messages.

A final detail to account for is the fact that the PIM-SM-DPF proposal builds SPTs from RP to multicast members. Certain protocols like NBM [11] also deploy the multicast tree by a recursive SPT algorithm, which attempts to develop alternative paths if the probed path cannot reach the members.

The PIM-SM-DPF exceeds the particular inter-domain condition of asymmetric routes. The model operates correctly in an inter-domain scenario with only this constraint, but the particularities of multiple paths between any two network nodes must be addressed. This issue is treated in the second modification proposal, which also addresses the first constraint.

2. PIM-SM-Inter-domain Tunnelling (PIM-SM-IDT)

If the inter-domain scenario contains multiple paths connecting nodes to different domains, the problem of multiple branch generation between any pair of tree nodes that converge may occur. This would generate multiple multicast stream replication that arrives at multicast members, and so a modification is needed to allow the PIM-SM to operate under these conditions without support protocols. This problem is illustrated in Fig. 4.

The proposed modification PIM-SM-IDT is based on two main ideas. First, a system for direct communication is implemented between the RPs of different domains, which allows them to establish inter-domain unicast tunnels. The second innovation confines multicast traffic distribution inside each PIM domain, deploying inter-domain multicast distribution by these unicast tunnels connecting the RPs.

The deployment of unicast tunnels to connect PIM domains is advantageous for eliminating the need for PIM routers in the inter-domain space. PIM routers are needed only in the RP entities and inside of the domains, which is where traditional multicast is performed. The unicast tunnel structure for confining traffic combines solutions described in [13], [19]. The former addresses the issue of multicast traffic confinement by the employment of special IPv6 multicast addresses. The latter describes a mechanism for RP-to-RP direct communication. A local RP exists in every domain for traffic confinement. Figure 5 shows the functional model of the PIM-SM-IDT. On the one hand, local RPs are distinguished from the others through attached multicast sources. This issue is executed by dispatching PIM-advertisement messages. On the other hand, local RPs catch PIM-join messages addressed to a group that is served by an external RP (blue continuous arrows) to generate PIM-RP_Join_to_RP messages and to perform unicast tunnels setup.

V. Simulation

1. OMNeT++ and Auxiliary Tools

This section presents the modelling and simulation of the PIM-SM-IDT and PIM-SM-DPF proposals. We describe the behavior of each individually and in comparison with unicast. We choose the discrete events network simulator OMNeT++ v3.3 [20] for this purpose. This network simulator is open source, and the central part of OMNeT++ is the kernel. Over the kernel, specific frameworks are deployed that aim to simulate a particular area. There are frameworks for fixed and mobile networks simulation. For example, for Internet and TCP/IP stack simulation, the so-called INET framework in [21] is used to implement our proposal.

The base structure of the INET framework is not complete enough for inter-domain scenarios modelling. We require a capability to define hierarchical networks and multiple network domains. This goal is achieved through the extension generated by the ReaSE tool [22]. This extension allows hierarchical routing and distinguishes between the router level and the autonomous system (AS) level. In addition, the tool contains a graphical user interface (GUI) for network definition and scenario generation.

An extension of the INET framework was performed to enable PIM-SM protocol simulation as well as incremental changes for PIM-SM-DPF and PIM-SM-IDT simulations.

2. Adaptation and New Elements

We performed modifications in the OMNeT++ and INET framework in several phases. We adapted the model to permit PIM-SM dynamic multicast simulation. The original INET model only allows DVMRP [7] and multicast simulation. The PIM-SM standard is enhanced by incorporating interaction messages, auxiliary control structures, physical and logical

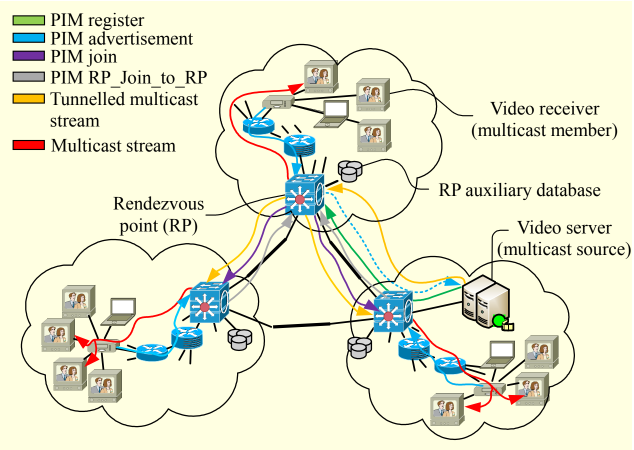

Fig. 5. PIM-SM-IDT proposal.

modules, and TCP/IP stack enlargement through additional C++ code. The new main element added to the model is the RP router, which centralizes the operations of control and multicast flow tree distribution. Other new elements include multicast members, multicast sources, PIM routers, and protocol messages. In addition, we have incrementally modified these base extensions for the PIM-SM-DPF and PIM-SM-IDT simulations, specifically the operational interaction patterns and protocol control messages.

One additional element implemented in the model for an auxiliary purpose is the collection of statistics, which makes possible the collection of centralized statistics from probes allocated throughout the network scenarios.

3. Simulation Scenarios

This section addresses the global integration of the new physical and logical elements in the context of the INET framework as well as the modelling of particularly important configuration parameters for the scenarios, such as physical links, router buffer sizes, and the modelling of PIM routers process delay. Finally, the sets of configuration parameters for the generated simulation scenarios (both multicast and unicast) are presented.

The router level and AS level topologies must be deployed separately and then subsequently connected to define an inter-domain network topology. The ReaSE tool can define both levels of hierarchy. The stub and transit domains are defined in the AS level. The router level contains three additional levels of hierarchy: core, gateway, and edge. Figure 6 presents the router level in OMNeT++ GUI.

The modelling of physical links remains unchanged in the ReaSE hierarchical physical links model. The assigned values to links in the modelled scenarios are presented in Table 1. In cells with only a “down” bitrate, the “up” bitrate is similar to the down one.

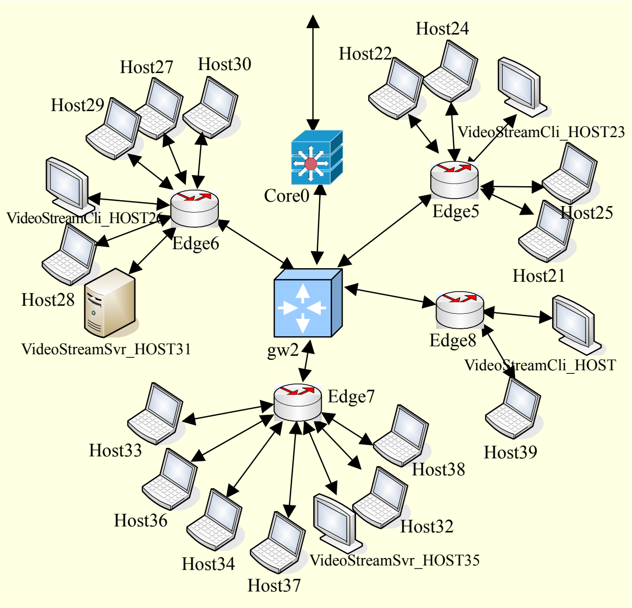

Fig. 6. INET PIM-SM intra-domain topology.

Table 1. Physical links configuration parameters.

	Hierarchy level					
Parameters	Transit-transit	Transit-stub	Core-core	Core-gateway	Gateway-edge	Edge-hosts
Bitrate (down/up) (Mbps)	10,000/	5,000/	2,500/	1,000/	155/	3/1

The placement of the PIM-SM main components are as follows. The RP is connected directly to a backbone router at the transit level because of the bandwidth requirement of these components. Multicast sources are connected via high bandwidth links from the edge to transit level with 10 Gbps links so that the bandwidth required in the unicast mode is not limiting. All routers in the modelled scenarios are PIM capable and are connected by point-to-point links. This kind of connection is deployed throughout all of the scenarios. Up to 10% of the total number of users can be multicast members, which is a requirement for PIM sparse mode operation. This constraint is maintained in the PIM-SM-DPF and PIM-SM-IDT models.

The router buffers and process delay are modelled according to [23], [24]. The former reports on a study about the sizing router buffers in the CeNTIE’s Australian backbone network. The latter examines the process delay in various backbone routers of Sprint’s global network and empirically models statistical distributions that describe the measurements obtained.

Table 2. Configuration parameters of scenarios.

Parameter	Value							
Autonomous systems	3			10			90	
Backbone nodes	1	2	3	2	3	4	3	4
Edge hosts	1k	5k	10k	5k	10k	50k	10k	50k
Multicast members	3%				10%			
Multicast groups	1 group			2 groups			4 groups	
Packet length	500 bytes			1,400 bytes			9,000 bytes	
Bitrates	416 kbps				1,428 kbps			
Simulation time	100 s							
Multicast sources	1 multicast source							
Members join pattern	Normal distribution $N(40,10)$							
Members location	Random							

Buffer sizes of 50, 40, and 25 packets used in each level of the hierarchy were used for core routers, gateways, and edge routers, respectively. This choice of values takes into account the results of [23] for the minimal requirements at the lower level of hierarchy for the core.

The steps for modelling the values with regard to the process delay in PIM routers are explained below. In the equations, L denotes the IP packet length in bytes.

$$\begin{aligned}\overline{d_{\text{router,min}}(L)} &= \frac{1}{3}\left(\overline{d_{\text{router,min,1}}(L)}+\overline{d_{\text{router,min,2}}(L)}+\overline{d_{\text{router,min,3}}(L)}\right)\\ &= \frac{1}{3}\left[(0.0213L+25)+(0.0089L+7)+(0.0192L+18)\right]\\ &= (0.0494L+50)/3\ (\mu\text{s}),\end{aligned} \tag{1}$$

$$\begin{aligned}\overline{d_{\text{router}}(L)} &= \left[\left(112/26+63/26+20/7+24/19\right)/4\right]\overline{d_{\text{router,min}}(L)}\\ &= 2.72\ \overline{d_{\text{router,min}}(L)}\ (\mu\text{s}),\end{aligned} \tag{2}$$

$$d_{\text{router}}(L) = \text{exponential distribution}(\overline{d_{\text{router}}(L)})\ (\mu\text{s}). \tag{3}$$

Three sets of experiments in which the links conditions and end connection points were varied are described in [24]. The minimum average thresholds were calculated at each test bed to obtain values for $\overline{d_{\text{router,min,1}}(L)}$, $\overline{d_{\text{router, min, 2}}(L)}$, and $\overline{d_{\text{router, min, 3}}(L)}$ corresponding to the average minimum processing delay for each set. By varying the packet length for the three sets, a linear function was obtained to determine the values for each set. Equation (1) was used to calculate the minimum average router delay from the average values for the three sets. The average router delay is obtained in (2) by weighting of the minimum and average observed delays for the three sets of experiments, with the additional constraint of no header packet processing. Finally, (3) shows the modelled router process delay as an exponential distribution with the average value of the process delay as a function parameter.

The execution of simulations is defined by specific scenarios that include concrete values for all of the configuration parameters. The ranges used for the scenarios are presented in Table 2. The service parameters are based on the study of several current Internet TV commercial services. The network parameters are values for typical networks that are feasible for calculation.

VI. Results

1. Definition of Parameters

In this work, we executed several sets of simulations based on the inter-domain scenarios defined in the previous section. The main goal of the simulations was to perform a comparative analysis between the PIM-SM standard and modified protocols in terms of the quality of service levels. The results presented in this paper include several network efficiency parameters for multicast and unicast performance assessment, that is, the PIM-SM standard, PIM-SM-DPF, and PIM-SM-IDT.

There are several interesting reports on the evaluation of unicast versus multicast network efficiencies, such as [25], [26]. The authors of [25] define a multicast versus unicast parameter to estimate efficiency in terms of bitrate consumption. This is a modification of a previously defined metric [27] and relates the number of multicast links to the unicast hops count for a given flow.

Two sets of parameters have been used to perform the current evaluation. The first set uses measurements directly obtained from OMNeT++ standard output vectors, which are collected by the *GlobalStatsManager* module. These primary parameters collect values for bitrates, end-to-end delay, and cumulated jitter parameters. In addition, the first set is used to establish the general framework for the second set of measures.

The second set of secondary parameters has been defined to estimate specific multicast efficiency in comparison with that of unicast. The parameters include bitrate, stretch, and setup time efficiency, which are described in detail next.

A definition for the bitrate efficiency parameter can be found in [25] and is shown in (4). This parameter measures the average bandwidth savings when multicast is used instead of unicast:

$$\delta := 1 - L_m / L_u\,, \tag{4}$$

where L_m represents the number of multicast links used in the whole scenario, and L_u indicates the number of unicast hops executed by the packets of content stream distributed in the scenario.

The stretch parameter measures the end-to-end average delay reduction when a multicast distribution is performed instead of a unicast one. This parameter is used in multicast overlay scheme efficiency estimation in [26] and is defined as

$$\tau := 1 - \overline{D} / \overline{d}\,, \tag{5}$$

where $\overline{D}$ and $\overline{d}$ are the multicast and unicast global average delays, respectively.

The third secondary parameter is the setup time efficiency estimator, which provides information on the setup time variation within unicast and multicast distribution schemes. The setup time is the time elapsed between the sending of a join request by a member (or the IGMP join message in multicast) and the reception of the first data packet from the source. Equation (6) defines the parameter:

$$\rho := 1 - \overline{T_s} / \overline{t_s}, \tag{6}$$

where $\overline{T_s}$ and $\overline{t_s}$ are the global multicast and unicast average setup times, respectively.

Although primary and secondary parameters have been calculated for all of the simulation scenarios, only the secondary parameters are taken into account. Because the secondary parameters are based on relationships between the primary ones, their values are more representative and can be used as references to validate our proposal.

2. Discussion of Results

Figure 7 shows the bitrate efficiency for a scenario with three autonomous systems with a variable number of final hosts connected to the network ranging from 1,000 to 10,000 and 3% and 10% membership. The membership percentage represents the percentage of final hosts connected to the multicast group. Both the PIM-SM-DPF and PIM-SM-IDT are good candidates to implement PIM-based multicast in an entire inter-domain scenario with regard to bandwidth consumption. The efficiency values are similar for the three variants of the PIM-SM. Higher efficiency rates were observed in comparison with those for unicast, which increase with the number of members connected to the distribution tree.

Figure 7 presents the average values collected from the entire scenario, but this type of presentation may mask operation problems related to inter-domain particularities. The existence of multiple paths between two inter-domain network points is problematic in the PIM-SM-DPF operation. Multiple shared tree branches converge in certain backbone routers, causing a stream to be replicated multiple times in the same branch.

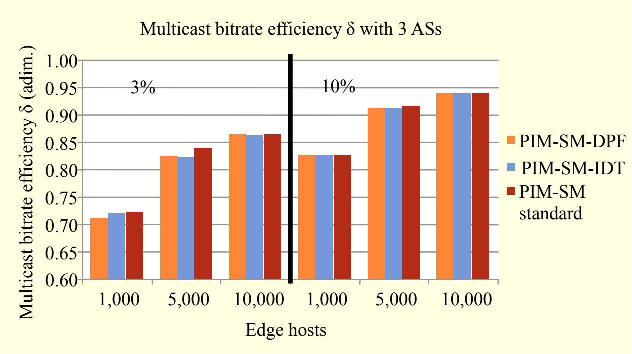

Fig. 7. Multicast versus unicast efficiency.

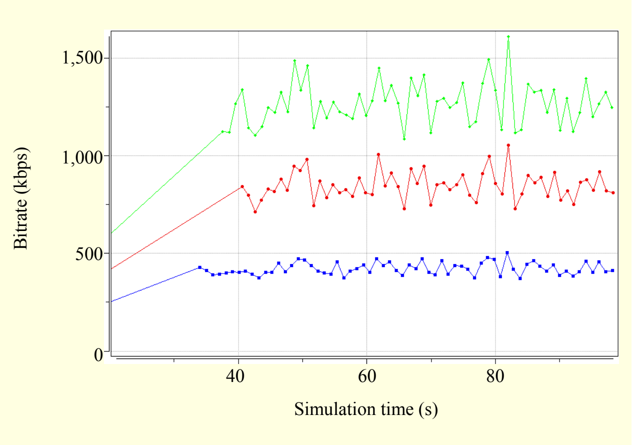

Fig. 8. PIM-SM-DPF bitrate at three multicast members.

This problem is illustrated in Fig. 8, which shows the PIM-SM-DPF multicast streams that reach three multicast members allocated on various domains at 90 autonomous systems and 10,000 hosts with a service at 416 kbps. Under these conditions, the streams represented by the red and green curves replicate the multicast stream two and three times, respectively.

The problem is completely addressed by the PIM-SM-IDT, which establishes unicast inter-domain tunnels between PIM domains, thus avoiding the convergence of the three branches. In this case, the streams arriving at each member are only one instance of the delivered continuous media stream (Fig. 9).

Figure 10 shows average stretch parameter values obtained for the scenario considered in Fig. 7. The stretch values increase with the number of members in the multicast tree, as observed by the improving bitrate. Higher stretch values for the PIM-SM-DPF/IDT than those with standard PIM-SM indicate an improvement in end-to-end delay. Again, we see that the

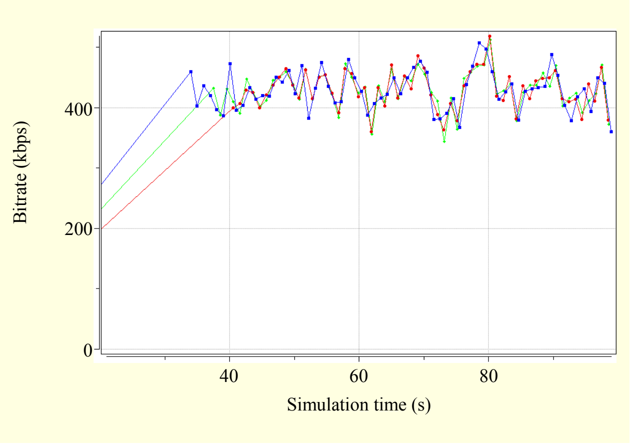

Fig. 9. PIM-SM-IDT bitrate at three multicast members.

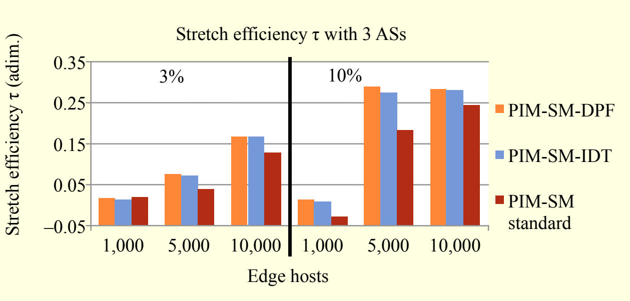

Fig. 10. Average stretch parameter values.

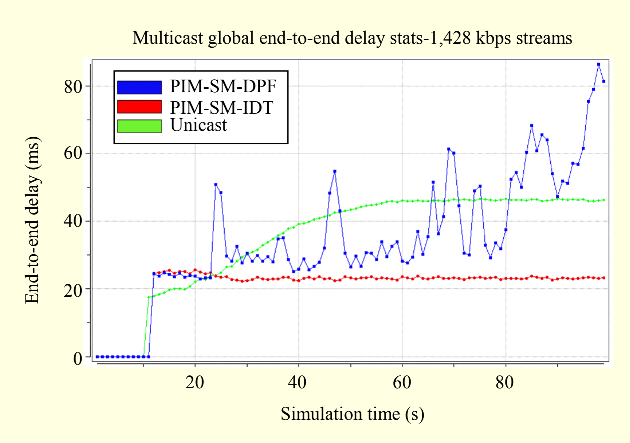

Fig. 11. Multicast versus unicast end-to-end delay.

modification proposals are suitable for inter-domain multicast distribution.

As for bitrate efficiency, stretch efficiency may mask operation errors when calculated in terms of average value over the entirety of the scenarios and the complete simulation time. In the case of end-to-end delay, the PIM-SM-DPF has higher delay values caused by the saturation of a few physical links in the lower level of hierarchy. This saturation is associated with the branch convergence problem.

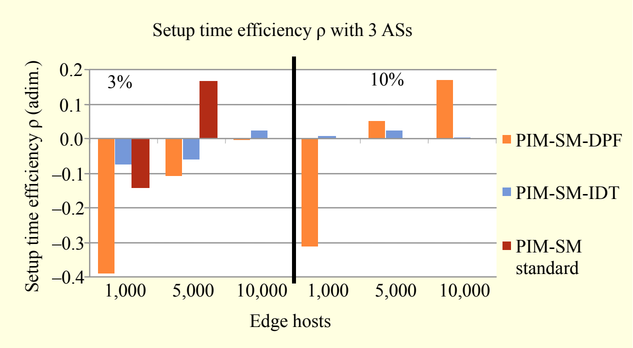

Fig. 12. Setup time efficiency.

Figure 11 shows the global average end-to-end delay in milliseconds over the entire simulation scenario and simulation time associated with PIM-SM-DPF and PIM-SM-IDT as well as the unicast case. The tested reference service is Internet TV, a high-quality continuous media delivery service at a bitrate of 1,428 kbps. The scenario includes 10 autonomous systems and 50,000 final hosts. The end-to-end delay growth and its high associated jitter for the PIM-SM-DPF (blue curve) are shown for the case of a 1,428 kbps multicast stream. The other curves represent PIM-SM-IDT (red curve) and unicast (green curve) delay values at 1,428 kbps.

We calculated the setup time efficiency parameter as the final secondary efficiency parameter. The multicast versus unicast comparison revealed higher values for the join times in multicast distribution mode for 5,000 members or less (see the negative values in Fig. 12). However, because the join time depends on the specific location of the RPs and that there were several RPs in the inter-domain scenario, it was not easy to identify a pattern or trend in the increment of the member number. We concluded that the variations are not significant enough to discard the PIM-SM modifications based on these results. Figure 12 shows the setup time efficiency for a scenario with three domains.

VII. Conclusion

In this paper, we introduced and discussed several existing solutions for multicast in the field of inter-domain networks. The PIM-SM standard protocol was chosen as the target protocol because of its ability to support continuous media distribution services, such as IPTV broadcast service. Moreover, it has been deployed [28].

Several modifications to the original IETF PIM-SM protocol are proposed. The main objective is to avoid the use of additional support protocols as much as possible to facilitate deployment and to solve problems that arise in inter-domain environments. Additional objectives are to improve performance and to evaluate the efficiency of the newly proposed multicast solutions versus the unicast case.

The first proposed modification, namely, the PIM-SM-DPF, implements the multicast tree construction while avoiding domain isolation and asymmetric routes. The second modification, called the PIM-SM-IDT, addresses the problems mentioned above and also prevents the existence of multiple routes.

The new protocols were evaluated using the simulation tool OMNeT++. The simulator was modified and enhanced to incorporate new classes and objects into its framework to use OMNeT++ on inter-domain networks.

After analyzing the simulation results, we concluded that the PIM-SM-IDT protocol is perfectly valid for operation as a multicast routing protocol in a full inter-domain scenario. The efficiency losses related to the original PIM-SM model are limited, and the PIM-SM-IDT even shows a higher efficiency in some circumstances. An additional advantage of the new model over the original is its ability to operate successfully in inter-domain networks without using support protocols. Its disadvantages are the complexity of operation and the necessity of a local RP on each PIM-SM domain in addition to the remote RP.

The simulator allows us to address new issues readily, such as more dynamic simulation scenarios with more than one source of data, especially PIM Source Specific Mode.

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