Efficient Planning of Satellite-Terrestrial Hybrid Networks for Multicast Applications

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Abstract— **As the satellite technology will be one of the main components of the Next Generation Internet (NGI), a naturally occurring question concerns the feasibility of providing an efficient satellite-based Internet access. In this paper, we are interested in the problem of the planning of satellite-terrestrial hybrid networks for the multicast transfer. We first develop an architectural model for such type of networks, then we define the problem and we propose a planning heuristic that determines the sub-optimal positions of satellite uplinks in a given terrestrial network. The proposed method minimizes the mean cost (the number of branches) of multicast trees for the unreliable multicast and the mean packet transfer delay for the reliable multicast. In addition, we develop a configuration policy of PIM-SM in hybrid networks concerning the choice of the list of Rendezvous Point (RPs) and the switching from the RP-routed tree to the shortest path tree. The obtained results demonstrate the ability of the proposed methods (the planning heuristic and the PIM-SM configuration policy) to improve the multicast performance criteria and to determine effectively the satellite uplinks positions using PIM-SM combined with UDLR (UniDirectional Link Routing).**

***Keywords*— GEO Satellite Links, Multicast Transfer, Optimization Heuristic, Multicast Routing Protocols, UDLR.**

I. INTRODUCTION

The growth of the traditional Internet and the availability of new users applications such as video on demand, tele-conference and IP telephony have led to several bottlenecks in the backbone networks. That's why we place currently severe demands on global telecommunications since constraints and limitations imposed by multimedia applications differ from those of traditional applications (telnet, ftp, web, etc.) in terms of network resources (delay, bandwidth, etc.) and then can not be efficiently executed in the traditional Internet.

Multimedia services need the deployment of new high-bandwidth communications links. If these applications are to be successfully implemented, infrastructure improvements must be immediate, cost effective and large geographical scale. The GEO satellites can provide these new applications to businesses and households quickly and over a wide area especially for multicast transfer. Indeed, a satellite-based solution provides immediate point-to-multipoint and point-to-point networks over short and long distances and improve access to audio, video, and other emerging multimedia services. The inherent broadcast traffic nature of GEO satellite suggests that the multicast might be easier to provide in satellite-based Internet access compared to the traditional Internet [15].

Several researchers have considered different issues in satellite-based Internet access [1], [11], [15]. They focus mainly on comparing this access to the traditional access so as to evaluate the benefits of GEO satellite links. However the issue of the efficient deployment of satellite links in the Internet such that the network performance criteria are optimized, while the satellite access cost is minimized has not been addressed in these works.

Our main focus in this paper is the problem of the planning of satellite-terrestrial hybrid networks for multicast transfer. Thus, given that GEO satellite resources are limited, it is necessary to determine the strategic positions in the Internet where to add GEO satellite uplinks. This problem consists of determining the strategic positions of GEO satellite uplinks that improve the performance of the multicast transfer. This is a network topology design

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problem which can be defined by a set of inputs, variables, goals and constraints. Given the terrestrial topology, the multicast groups, and the multicast traffic, we should determine satellite uplinks positions which optimize the mean cost of multicast trees for unreliable multicast transfer and the mean packet transfer delay for reliable multicast transfer and we should ensure that the network cost does not exceed the available budget.

We do not claim that the strategies we pick here are the optimal. It is not the purpose of this paper to find the optimal methods to plan hybrid networks, we only want to study the added value of the efficient use of satellite links for the multicast transfer by comparing different methods and strategies.

The remainder of the paper is organized as follows. In Section 2, we describe the hybrid network architecture that we consider. Section 3 details the problem of the planning of hybrid networks for multicast applications and the proposed resolution strategies. The configuration policy of PIM-SM [6] for hybrid networks will be presented in Section 4. In Section 5, we discuss results obtained for the unreliable multicast transfer as well as the reliable multicast. Finally, Section 6 concludes the paper by summarizing results and presenting future work.

II. Satellite-Terrestrial Hybrid Networks Architecture

Prior to studying multicast transfer optimization problem during the deployment of GEO satellite links in the Internet, a hybrid network architecture must be specified. We mean by hybrid network a terrestrial network connected to a GEO satellite with **on-board multiplexing** capability offering a high bandwidth shared by satellite uplinks and a broadcast downlink toward terrestrial receivers. A satellite uplink is an unidirectional wireless communication link which connect two nodes (router, host, etc.) via the GEO satellite. In the remainder of this paper we use the following terminology [5]:

- Receiver: a node that has a satellite receiver station.
- Feed: a node which has the capability to send data via a satellite uplink.

The Internet today is an inter-connection of Autonomous Systems (AS) (called also domains). An AS is a connected group of one or more IP prefixes run by one or more network operators which has a **single** and **clearly defined** routing policy [8]. In this section, we describe an architecture for one terrestrial-satellite hybrid AS composed of terrestrial and satellite communications links.

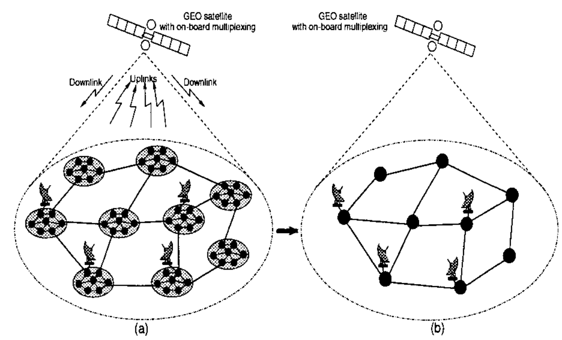

Fig. 1. Satellite-Terrestrial Hybrid Network Architecture
(a) General architecture (b) Simplified architecture

We assume that the terrestrial part of the hybrid network consists of several regional high-speed networks (or. clusters) connected with low-speed terrestrial communication links (see Fig. 1a). A limited number of uplinks can be offered by the GEO satellite and then the number of regional networks will be much more than that of feeds (satellite uplinks).

In the proposed architecture, we assume that all feeds and receivers are connected to the Internet via one of their bidirectional interfaces so as a receiver and a feed can communicate with each other using the bidirectional terrestrial network. Thus, a receiver which want to access to an Internet server, sends its request via terrestrial network and using UDLR mechanism [5] it may receive data from the broadcast satellite downlink.

We may not have a feed in each regional network. On the other hand, there is no need to have more than one satellite uplink in each cluster because the high connectivity within the cluster. So, we limit the number of satellite uplinks in each cluster to one since regional networks are supposed to be high-speed networks and the feed will be used only to access other nodes which belong to another regional network while the communication inside the regional network will be done through terrestrial communication links. However, considering that the satellite receiver station is not costly comparing to that of feed, we assume that each node has the capability to receive data from the broadcast satellite downlink. For these reasons we give in Fig. 1b a more simplified architecture in which each cluster is considered as one terrestrial node.

III. Hybrid Networks Planning Problem

We argue that the use of GEO satellite links in the Internet will be a profitable and a generalized solution only if we ensure a good deployment of this new technology. In this section we detail the problem of determining where to add GEO satellite uplinks in order to improve the mean cost of multicast trees for the unreliable multicast transfer and the mean transfer delay for the reliable multicast and to not exceed the given budget (Section III-B arguments the choice of these performance metrics).

Our proposed planning heuristic starts by evaluating the performance of the initial terrestrial topology and then it executes two main steps which are the finding of a sub-optimal position where to add the current satellite uplink and the performance evaluation of the new hybrid topology. In the following sub-sections, we detail these two main steps.

A. Satellite Uplinks Positions

We can imagine several techniques to determine the position where to add the satellite uplink. The strategies that we compare here are:

- A random position
- One of the sources of the multicast group having the costly multicast tree
- The node close to all the multicast sources
- A multicast source belongs to many multicast groups

It is evident that each technique listed above minimizes the mean cost of the multicast trees since multicast routing protocol will take into account the presence of the new satellite communication uplink when building the multicast delivery trees. In the worst case, we will obtain the same mean cost of multicast trees even after adding a satellite uplink in the selected position.

Let us now explain another more sophisticated method. For each multicast group, we determine a particular multicast source that we called CMT (*Center of Multicast Tree*). The CMT_g of group g is that source which is closest to all other multicast sources of the same group. The distance is evaluated in number of branches for the unreliable multicast transfer and it is the mean packet delay for the reliable multicast transfer. At this step, we introduce the following definitions:

- CMT List: we mean by CMT List of a specific multicast group, the list of sources ordered considering their mean distance to each other.
- CMT Matrix: we mean by CMT Matrix, the matrix having $G * S_{max}$ elements where G is the number of groups and S_{max} is the maximal number of sources per multicast group. This matrix is composed by all CMT List. The CMT List of multicast group g is the row g of the CMT matrix.

After determining the CMT List for each multicast group, the next step is to select a source among the CMTs of all multicast groups. We propose to arrange the CMT matrix in order to determine the CMT in which we add the satellite uplink. We believe that an arrangement per column can guarantee the **fairness**[1] between multicast groups. Then for each column, we consider the multicast group composed by nodes of this column[2] and we replace it by the CMT List of this group. As result, we will obtain an arranged CMT Matrix which will be processed successively column by column and row by row until we find a CMT which is not connected directly to a satellite uplink. This position is considered as the sub-optimal one for the current iteration of the planning heuristic.

B. Performance Evaluation Criteria

The second step of the planning heuristic is the performance evaluation of the obtained topology in each iteration.

B.1 Unreliable multicast transfer

The unreliable multicast transfer does not impose that all group members receive correctly each packet sent by the multicast source. Since existing multicast routing algorithms (*source-based shortest-path trees* and *mini-*

[1] The fairness measures the distribution of satellite uplinks between the multicast groups. It will be expressed in Section 5.

[2] These nodes belong to different multicast groups.

mal spanning trees) use the number of communications branches as a basic metric in multicast routing, we consider the number of branches as the cost of a multicast tree. In each iteration of the planning method, we compute the mean cost of multicast trees by dividing the sum of all source-based delivery tree cost by the number of multicast sources.

B.2 Reliable multicast transfer

Unlike the unreliable multicast transfer, a packet sent by a reliable multicast source should be correctly received by each receiver belonging to the same group. Noting by $\overline{R(G)}$ the number of retransmissions of a multicast packet until it will be received by all receivers and by t_r the mean transmission delay of a multicast packet. Then, the mean transmission delay of a reliable multicast packet is:

$$T_{trans} = t_r + t_r * \overline{R(G)} \qquad (1)$$

and the propagation delay is:

$$T_{pro} = RTT_m + RTT_m * \overline{R(G)} \qquad (2)$$

where RTT_m is the maximal RTT (*Round Trip Time*) between source and receivers. Using (1) and (2), we obtain the expression of mean transfer delay of a reliable multicast in a hybrid network as follows:

$$T = T_{trans} + T_{pro} = t_r + RTT_m + (t_r + RTT_m) * \overline{R(G)} \qquad (3)$$

Biersack and Nonenmacher have given in [13] an approximation of the number of receivers that have correctly received a multicast packet sent by the source and the mean number of transmissions until all receivers receive the packet. They concluded that:

$$\overline{R(G)} \simeq PL \qquad (4)$$

for $PL \leq 1$, where L is the number of links in the multicast tree and P is the link loss probability due to loss in routers buffers. We use this approximation to compute the mean transfer delay given by (3).

IV. PIM-SM CONFIGURATION POLICY FOR HYBRID NETWORKS

In considering a routing protocol to be used for multicasting in terrestrial-satellite hybrid networks, one has to carefully look at the issues unique to this type of network and make use of the broadcast nature of GEO satellites.

The existing multicast routing mechanisms broadcast some information and therefore do not scale well to groups that span the Internet. Multicast routing protocols like DVMRP [14] and PIM-DM [4] periodically flood data packets throughout the network. MOSPF [12] floods group membership information to all the routers so that can build multicast distribution trees. Protocols like CBT [2] and PIM-SM [6] scale better by having the members explicitly join a multicast distribution tree routed at a core router. CBT was proposed in the research literature and standardized by the IETF but, it has not been significantly deployed because it exhibits greater traffic concentrations [3].

Since PIM-SM is well suited to large wide-area networks, it can effectively used in hybrid networks where there is a great number of regional networks connected to a GEO satellite.

PIM-SM requires routers that are directly attached to downstream members to join a sparse-mode distribution tree by transmitting explicit join messages to the group's primary Rendezvous Point (RP) which acts the root of the tree. PIM-SM creates a shared, RP-routed distribution tree that reaches all group members. PIM-SM provides also a mechanism to switch from a RP-routed tree to a shortest path tree (SPT).

Using PIM-SM effectively in hybrid networks depends on our capacity to: (1) manage the choice of the RP of each multicast group, and (2) configure the policy used by group members to switch from a RP-routed tree to a SPT.

A. RP Placement

The *bootstrap mechanism* used in PIM-SM employs an algorithmic mapping of multicast group to rendezvous point address, based on a set of available RPs distributed throughout the network by the dynamically-elected BootStrap Router (BSR) from a list of Candidate-BSRs

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[6]. Routers belonging to the set of Candidate-BSRs or Candidate-RPs should be manually configured in the network [6]. For hybrid networks, we assume that all CMTs are configured as Candidate-BSRs and Candidate-RPs[3] (see Section III-A for more details about how we compute the CMT Matrix).

In order to profit from satellite link broadcast nature, the RP placement policy that we recommend in such type of networks is related to the positions of satellite uplinks (feeds) in the terrestrial network. For each multicast group we process as follows to select the RP:

- If there is a feed which is a multicast source of the group, it is chosen as the RP of this group. If there is more than one feed belonging to the group, the feed which is the first one in the CMT List of this group will be elected as the RP.
- If there is no feed belonging to the multicast group, it is recommended to choose the closest feed for multicast sources as the RP of this group. If there is more than one feed in the hybrid network, the feed which has the highest priority for this group will be elected.

Practically speaking, this policy of RP placement in a hybrid network can be achieved by effectively choosing the priority value of each RP in the Candidate-RP message sent to the BSR.

B. *Switching from a RP-routed tree to a SPT*

PIM-SM specification [6] does not specify a fixed policy to switch from the RP-routed tree to the SPT, but it recommends that the router monitors data packets from sources for which it has no source-specific multicast route entry and initiates such an entry when the data rate exceeds the configured threshold. Let us apply this method to a hybrid network. If at least one satellite receiver that is a member of the multicast group decides to switch to the SPT and when the SPT contains a feed, all satellite receivers will receive multicast packets sent by the source. Multicast receivers that are still using the RP-routed tree will receive a **duplicated packet**: a copy from the terrestrial interface belonging to the RP-routed tree and another copy from the satellite interface. We propose a switching policy that can be used effectively in to avoid the packet duplication in a hybrid network. This policy consists as follows:

- If the source is a feed, it makes sense for all satellite receivers members to join source-specific tree and prune the source's packets off the shared RP-centrated tree since it forwards data to members via the satellite link. Or, the RP triggers Register-Stop messages in response to Registers sent by the source only if the RP has no downstream receivers for the group, or if the RP has already joined the (S,G) tree and it receiving the data packets natively. That's why we recommend that all satellite receivers members join directly the source. This can be done by properly configured the threshold maintained by the router. For example, we can attribute for each (S,G) a threshold value close to zero to guarantee that each satellite receiver member switch to the SPT when the source is a feed.
- if the source is not a feed, it is not desired to switch from the RP-routed tree to the SPT especially when the RP is a feed. Multicast packets will be sent by the source to the RP via the UDLR tunnel [5]. The threshold maintained by each member for the (S,G) entry should be then greater enough to avoid the switching.

A major advantage of the use of PIM-SM in hybrid networks is the option switching from the RP-shared tree to the Shortest-Path-Tree (SPT). We believe that PIM-SM, combined with UDLR, grants an efficient use of terrestrial communication links resources considering that multicast packets are sent via the satellite link when it is properly configured.

V. Simulation Methodology and Results

We performed simulations to study and compare the different satellite uplinks positions selection methods proposed in Section III-A and to analyse the improvement added by the PIM-SM configuration policy presented in Section IV.

The terrestrial topology is randomly generated and it has a connectivity equal to 3; i.e, each router is connected to at least three different routers. A multicast group is composed by sources and receivers nodes which are cho-

[3] [6] recommends that C-BSRs should be equal to C-RPs.

sen randomly[4]. The size of each multicast group is generated randomly between 2 and the network size. We compute, using PIM-SM (see Section IV), per multicast group the multicast delivery trees.

In the planning process, we add in each iteration a new satellite uplink until we reach the final configuration. This configuration is obtained when the addition of a new satellite uplink does not improve the performance criteria or when the number of feeds reaches the maximal number to add.

We show in Fig. 2, the mean cost of multicast trees vs. the number of satellite uplinks added for each satellite uplink position selection method.

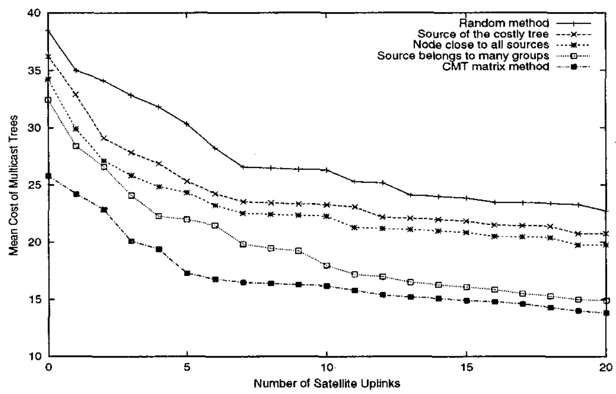

Fig. 2. Mean multicast trees cost as a function of the number of satellite uplinks. The network size is 1000 and the number of groups is 100.

It can be seen that the addition of satellite uplinks improve considerably the mean cost of multicast trees since an added satellite uplink decreases the multicast tree cost of certain groups because PIM-SM configuration imposes to certain groups to use the new feed as the root of the multicast tree (see Section IV). Also, it is clear from the plots of Fig. 3 that all methods improve the mean cost of multicast trees, but the improvement offered by the CMT matrix method is much better than that offered by other methods.

Let us look at the fairness property of the positions selection methods. We define the fairness coefficient as $F = \frac{(\sum_{g=1}^{g=N_G} u_g)^2}{N_G \sum_{g=1}^{g=N_G} u_g^2}$ where N_G is the number of multicast groups and u_g is the number of satellite uplinks in the group g. As shown in Fig. 3, in the addition of the 8 first satellite uplinks, all the methods have approximately the same behaviour. However, only the CMT matrix method provides a fairness coefficient that increase linearally in function of the number of the satellite uplinks added in the network and which becomes close to 1 when the number of satellite uplinks close to the number of groups.

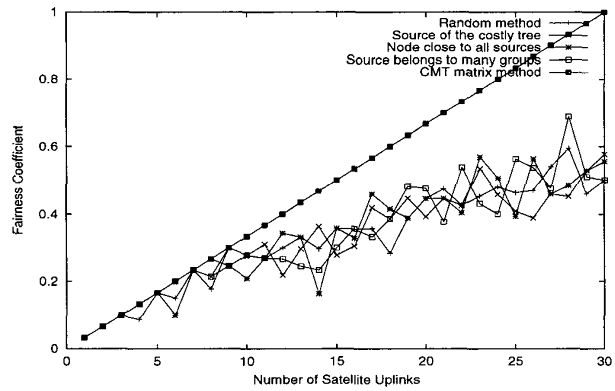

Fig. 3. Fairness coefficient as a function of the number of satellite uplinks. We generate 30 multicast groups and one source per group in a 1000 nodes network.

We turn our attention to the performance evaluation of the proposed PIM-SM configuration policy. We suppose that we use the CMT matrix method as the satellite uplinks positions selection method and we plot in Fig. 4 the mean cost of multicast tree obtained by the standard PIM-SM configuration policy and our proposed policy. Curves show that our PIM-SM configuration policy minimizes much better the mean cost of multicast trees than the standard method.

We plotted in Fig. 5 the variation of the mean transfer delay of reliable multicast packet in function of number of satellite uplinks added in the terrestrial network. The transmission time of a multicast packet, of 0.015625 secs with a fixed packet size of 1000 bits, corresponding to a maximum sending rate of 64 kbits/s was used for terrestrial link and that of 0.0005 secs corresponding to a maximum sending rate of 2 Mbits/sec was used for satellite

[4]In [7] we give more details about the generated topologies.

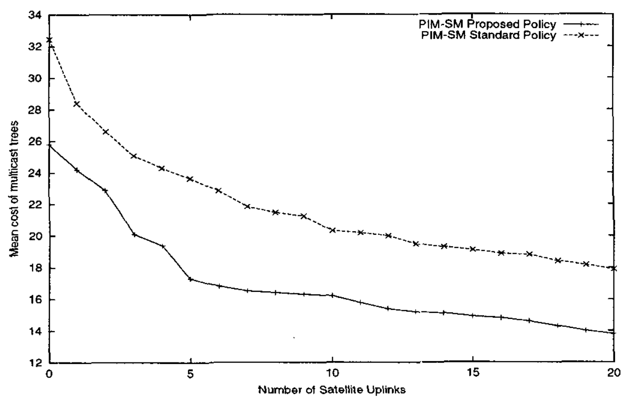

Fig. 4. Mean cost of multicast trees as function of the number of satellite uplinks for different PIM-SM configuration policies. We use the CMT matrix method us the positions selection policy.

link. A loss probability of 0.001 and 0.03 was assumed for satellite and terrestrial links respectively, representative of losses on the MBONE [10]. The satellite delay was assumed to be 250 ms.

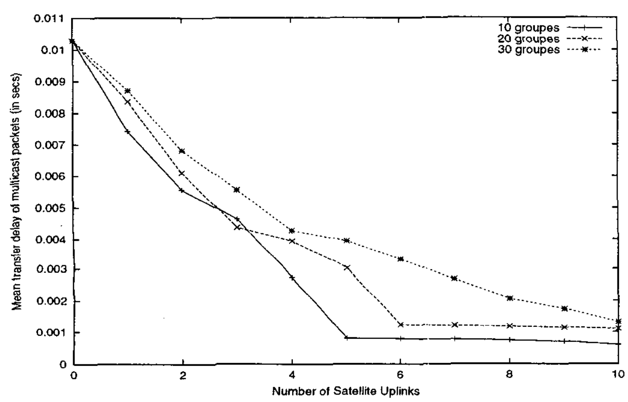

Fig. 5. Mean transfer delay versus the number of satellite uplinks for different sizes of multicast groups

We notice that the addition of satellite uplinks improve in the three cases (10 groups, 20 groups, and 30 groups) the transfer delay until reaching a specific threshold which increases with the number of reliable multicast groups. Indeed, in the case of 10 groups, this threshold is equal to 5 and it is equal to 6 in the case of 20 groups whereas it is equal to 2 when we have 30 groups.

VI. CONCLUSION

In this work, we have introduced the problem of GEO satellite links deployment in the Internet. We have particularly investigated the optimization of multicast transfer. We have developed a terrestrial-satellite hybrid network architecture composed with two parts: a terrestrial one which composed with connected high-speed communication clusters and a satellite part composed with GEO satellite links. The proposed optimization method determines the positions of satellite uplinks which minimize the mean cost of multicast trees for the unreliable multicast transfer and the mean transfer delay of multicast packet for the reliable multicast transfer. A configuration policy of PIM-SM has been developed and it has two main benefits. First, it builds a delivery tree where members receive data from the broadcast satellite downlink either using a RP-routed tree or a shortest path tree. Second, it minimizes the multicast traffic load in the terrestrial network so as the safe terrestrial bandwidth will be used by unicast applications or, in general, by applications having requirements that not verified by the satellite link. A quantitative study of multicast transfer metrics demonstrates that the use of satellite links optimize multicast transfer only if we correctly choose where to add satellite uplinks by considering positions of multicast sources.

Future work will be investigated in order to study the efficient planning of hybrid networks for unicast (best-effort and guaranteed) applications and to propose a global planning heuristic that take into account different types of applications. In [7], we have already proposed some basic approaches able to plan satellite networks for divers applications.

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