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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 optimal satellite-based Internet access. In this paper, we are interested in GEO satellite links deployment in the Internet by addressing the problem of terrestrial-satellite hybrid network optimization for which we propose a general architecture.

We devide the general optimization problem into several sub-problems which can be resolved separately. Each sub-problem treats a specific type of traffic and it is defined by a set of inputs, variables, goals, and constraints. The global GEO satellite links deployment optimization heuristic that we propose attempts to determine the optimal hybrid topology which minimizes performance metrics such as delay, throughput, call blocking probabilities, and network cost. Two main steps compose the proposed heuristic: performance evaluation step and satellite uplink position finding step. During the first step we try to determine values of performance metrics of studied traffic and in the second one, we look for the optimal position where to add the current satellite uplink in order to optimize performance criteria.

We present in details a case study dealing with multicast traffic optimization during the deployment of GEO satellite links in the Internet. 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. This policy provides an optimal use of satellite links for multicast transfer. The obtained results demonstrate the ability of the proposed optimization method to improve multicast performance criteria and to determine effectively satellite uplinks positions using PIM-SM combined with UDLR (UniDirectional Link Routing).

Key-words: GEO Satellites Links, Quality of Service, Analytic Model, Optimization, Multicast Transfer, UDLR.

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Optimization de Deployment des Liens Satellites GEO dans l'Internet

Résumé : Vue que les liens satellitaires seront certainement une partie intégrante de la Nouvelle Génération de l'Internet (NGI), une question naturelle concerne la faisabilité de fournir un accès optimal à Internet via un satellite. Dans ce papier, nous nous intéressons au déploiement des liens satellites GEO dans Internet et ceci via l'étude du problème d'optimisation des réseaux hybrides (terrestre et satellite) et pour lesquels nous proposons une architecture d'interconnexion générale.

Nous divisons le problème général d'optimisation en un ensemble de sous-problèmes que peuvent être résolus séparément. Chaque sous-problème traite un type spécifique du trafic et il est défini en un ensemble des données, variables, objectifs, et contraintes. L'heuristique global d'optimization que nous proposons permet de déterminer la topologie hybride optimale qui minimise les métriques des performances telles que: le délai, le débit, le blocages d'appels garantis, et le coût du réseau. Deux étapes principales compose l'heuristique proposée: l'étape d'évaluation des performances et l'étape de la détermination de la position optimale du lien satellitaire montant. Durant la première étape, nous calculons les valeurs des métriques des performances du trafic étudié, et dans la seconde étape, nous déterminons la position optimale où il faut ajouter un lien satellite montant afin d'optimiser les critères des performances.

Nous présentons en détails une étude de cas concernant l'optimisation du trafic multicast durant le déploiement des liens satellites GEO dans l'Internet. Nous dévéloppons une politique de configuration de PIM-SM dans un réseau hybride pour le choix de la liste de Rendezvous Point (RPs) et la commutation de RP-routed tree vers le shortest path tree. Cette politique offre une utilisation optimale des liens satellitaires pour le trafic multicast. Les résultats obtenus montrent la capacité de la méthode d'optimization proposée d'améliorer les critères des performances du trafic multicast et de déterminer efficacement les positions des liens satellitaires montants en utilisant PIM-SM et UDLR (UniDirectional Link Routing).

Mots-clés : Liens Satellites GEO, Qualité de Service, Modèle Analytique, Optimisation du Transfert Multicast, UDLR.

1 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 will 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. 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. Used combined with ADSL technology, this access allows end-users to receive data with a high rate even they do not have a satellite receiver station.

Several researchers have considered different issues in satellite-based Internet access [3], [14], [29]. They focus mainly on comparing this access to the traditional access so as to evaluate benefits of GEO satellite links. However the issue of the optimal deployment of satellite links in the Internet such that the network performance criteria are optimized, while the satellite access cost is minimized is not addressed in these works.

In the Fifties, researchers have studied telephonic networks design problems with the goal to determine the optimal configuration which minimizes end-to-end calls blocking probabilities [1]. The resolution approach was to consider arrival calls as a Poisson process and to look for network variables values (topology, capacities, cost, etc.) which give lower calls blocking probabilities and that the network cost does not exceed a given budget.

By the end of 1960 and the begin of 1970 [17], researchers were interested to packet switching networks design problems and in particular the ARPANET network. In this type of networks, calls blocking probabilities has no significance because a source-destination route is not a circuit but it is established during packets transfer. Users main source of dissatisfication was the mean packet transfer delay in the network. Therefore, packet switching networks design problems have been widely studied and several resolution algorithms and heuristics have been proposed [13] and [15].

These algorithms are based on some assumptions such as packets poisson arrivals of packets and independence assumption of Kleinrock[1][13]. Many recent works such as [25] and [26] show that these assumptions are not verified in current communication networks. In [27], [16] and [11] authors have tried to find others models that can model efficiently recent applications traffic. Also, with the appearance of new communication technologies and the introduction of Quality of Service (QoS) requirements, other works have interested to multiservices networks design [18], [24].

A GEO satellite's ability to provide communications infrastructure for whole regions and continents imposes the service providers to ensure an optimal use of their available satellite uplinks in order to be efficiently connected to their clients and to offer them a good Internet access. Then the use of GEO satellite links in the Internet will be a profitable and a generalized solution only if we ensure an optimal deployment of this new technology [3]. Thus, given that GEO satellite resources are limited, it will be necessary to determine the optimal positions in the Internet where to add GEO satellite uplinks.

The main intent of this paper is to define GEO satellite links deployment problems and to propose a general resolution method. The approach we adopt is to formulate a general architecture of an hybrid Internet and to determine performance criteria that we should optimize during the resolution process. We describe the general deployment problem and we extend our approach to cope with

[1]Packets omiss their identity after their arrival to a node which rebuilds them using an exponentionnal distributed lenght.

networks where different classes of service and mode of transfer (unicast and multicast) are provided to end users. Considering that we are interested in multiservices communication model since it will be the basic model of future networks, we divide the general deployment problem to sub-problems. Each sub-problem has as goal to find strategic satellite uplinks positions which optimize performance criteria of a specific type of traffic. This division allow us not only to decrease the complexity of the resolution of the general deployment problem but also to propose a specific resolution method for each type of traffic.

The rest of the paper is organized as follows. In Section 2, we describe our proposed hybrid network model which composed of two parts: terrestrial part and satellite part. In Section 3, we present a traffic model that we should take into account during the hybrid network design process. Section 4 enumerates all inputs, variables, constraints and goals that we need to define in Section 5 hybrid network optimization problems. Our resolution heuristic is illustrated in Section 6. Section 7 details the problem of multicast traffic optimization and explores the proposed resolution method. Finally, Section 8 concludes the paper by summarizing results and presenting our future work in the area of GEO satellite links deployment in the Internet.

2 Hybrid Network 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 [12]:

- UniDirectional Link (UDL): a one way transmission link. In our case it is a GEO satellite link.
- Receiver: a node that has a satellite receiver station.
- Feed: a node which has the capability to send data via an UDL.

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 [10]. In this section, we describe an architecture for one terrestrial-satellite hybrid AS composed of terrestrial and satellite communications links.

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 Figure 1(a)). 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 [12] 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

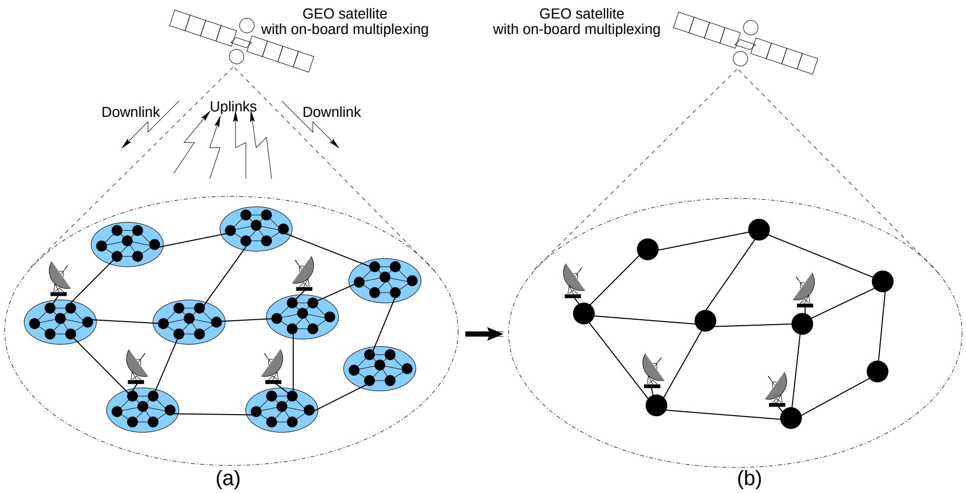

Figure 1: Terrestrial-satellite hybrid network architecture (a) General architecture (b) Simplified architecture

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 Figure 1(b) a more simplified architecture in which each cluster is considered as one terrestrial node.

A hybrid network is represented by a weighted digraph $G = (V, E)$, where V denotes the set of hybrid network nodes and E the set of communication links that connect the nodes. Of course, a communication link can be a satellite link or a terrestrial link. Considering the broadcast capability of the GEO satellite, we suppose that we have only one satellite downlink. $|V| = N$ and $|E| = M$ denote the number of nodes and links in the hybrid network, respectively. Associated with each link are parameters that describe the current status of the link, for example the average link delay, the link cost and the bandwidth available on the link. We term these parameters *link state*. Similarly, associated with each node are parameters representing the current status of the node, for example routing tables. We term these parameters *node state*. Link states and node states constitute the *hybrid network state*.

The hybrid network is supposed to deliver different types of traffic which will be discussed in next section.

3 Traffic Model

The transformation of the Internet to an important commercial infrastructure has modified customers needs in terms of security, performance and service requirements. Unfortunately, the best-effort service class remains the only class offered currently in the Internet. In this service, all packets are examined by the same way in all network nodes. A congested node may decrease the performance and even cause packets loss. However, with the development of new types of applications that need a service level higher than best-effort, it has been necessary to design new mechanisms and new approaches allowing the guarantee of service to this type of applications.

The Integration of satellite links in the Internet allows the deployment of multimedia applications such as information dissemination and broadcast, videoconferencing and video distribution, information retrieval and interactive gaming. However, performance varies according to applications because their requirements on network bandwidth and responsiveness, their tolerance to communication noise, and their implementation techniques are very different. The hybrid network proposed in Section 2 should be capable to deliver users applications according to their requirements.

In our traffic model, we suppose that we have two classes of service: best-effort service and guaranteed service. The traffic generated by best-effort applications has no special requirements and that by guaranteed applications has different requirements in network resources. The inherent broadcast nature of GEO satellite suggests that multicast might be easier to provide in hybrid networks compared to traditional Internet. That's why we propose to distinguish between applications traffic according to their transfer mode which can be unicast or multicast.

As shown in Table 1, we propose to study separately four types of traffic. Each type of traffic is defined by its class of service and its transfer mode and so it has a specific performance metric. For best-effort service we suggest the mean transfer delay as the potential performance metric of unicast transfer and the mean cost of multicast trees as the performance metric of multicast transfer. Considering that guaranteed service guarantees both delay bounds and bandwidth availability, we propose to consider calls blocking probabilities as the analytic performance metric for unicast guaranteed applications. A guaranteed call is blocked if network resources required by this call can not be offered by one or more communication links between the source and the destination. Since guaranteed multicast applications require a reliable multicast transfer, the mean transfer delay of a multicast packet is the performance metric that we propose to this type of traffic. Using an analytic model, this metric will be expressed in function of the mean number of retransmissions of a multicast packet until it will be received correctly by all receivers.

Class of Service	Transfer Mode	Performance metric
Best-effort Service	Unicast	Mean transfer delay
	Multicast	Mean tree cost
Guaranteed Service	Unicast	Call blocking probabilities
	Multicast	Mean multicast packet transfer delay

Table 1: Types and performance metrics of traffic

In order to take into account all types of traffic suggested, we consider the link communication model presented in Figure 2 and which is applicable for terrestrial as well as satellite links. We assume that the mean number of best-effort packets arrived to link j is equal to λ_j^{tb}packets/second. Calls belong to guaranteed service class will share every link of the hybrid network by a manner which depends on admission policy used.

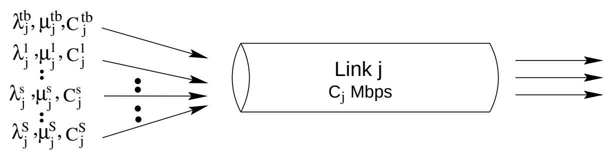

Figure 2: Communication link model

The arrival process of a guaranteed class s is supposed to be a Poisson process with an arrival rate equal to λ_j^s calls/second and the holding time of class s calls is assumed to follow a distribution function having a mean equal to $1/\mu_j^s$. During the life period of a class s call (or connection), a rate equal to C_j^s is allocated to this connection and it is liberated just after the end of the call.

4 Optimization inputs, variables, constraints and goals

We point out that our main goal is to ensure an efficient deployment of broadcast satellite links in the Internet. It should be possible if we determine where we add satellite uplinks in order to improve network performance.

Based on the network and the traffic models presented earlier, we enumerate, in this section, respectively inputs, variables, goals and constraints of optimization problems of GEO satellite links deployment.

4.1 Optimization Inputs

4.1.1 Terrestrial topology

The terrestrial topology is a fundamental input to all GEO satellite links deployment problems presented in this paper. It describes the terrestrial network architecture which will be modified by adding GEO satellite links in strategic positions.

As we have mentioned in Section 2, the terrestrial topology is supposed to be composed by high-speed regional networks connected by low-speed communication links.

4.1.2 Multicast groups

A multicast group is composed by a set of network nodes called group members. A member may be a sender (or source), receiver (or destination) or sender and receiver at the same time.

Multicast groups are represented by a group matrix (noted Π) which is composed by N rows and G columns. The element Π_{ig} is equal to 1 if the node i belongs to group g and it is equal to 0 if not. We distinguish between reliable multicast groups and unreliable multicast groups considering that they don't have the same performance metric. We note by Π_r the reliable multicast groups matrix and Π_{nr} the unreliable multicast groups matrix.

4.1.3 Network load

Network load is, by definition, the mean quantity of traffic in the network at a given time. It is equal to the sum of traffics generated by different types of users applications. It is one of the important network state parameters and it is described by the following elements:

- **Best-effort traffic matrix:** Best-effort traffic matrix (noted Γ_{tb}) is a fundamental input of all network design problems. The element γ_{kl}^{tb} of this matrix gives the mean number of best-effort packets per second sent by node N_k to node N_l.

- **Calls matrix:** For guaranteed classes, we interest to the mean number of connections (or calls) between each source and each destination. This choice is justified by the fact that the performance metric of the guaranteed class is the call blocking probability. We note by Γ_s the calls matrix of the guaranteed class number s. The element γ_{kl}^{s} of this matrix gives the mean number of calls of class s sent per second by node N_k to node N_l. In addition of calls matrix, the requirements of each guaranteed class in terms of bandwidth, delay and loss rate are also fundamentals inputs to guaranteed traffic optimization during the deployment of GEO satellite links.

- **Multicast traffic:** Multicast traffic can be described by two traffic matrix: the first one (noted Γ_r) for the reliable multicast and the second (noted Γ_{nr}) for the unreliable multicast. Every matrix is composed by N (number of nodes) rows and G (number of groups) columns. The element (n, g) of each matrix represents the mean number of multicast packets sent in one second by node n to group g. Noting that referring to multicast standard model [6], a node can send packets to a multicast group even it does not a member to this group.

The network load is determined, in general, by using traffic measurement tools in the case of an existing network and it is estimated in the case of the design of a new network.

4.2 Optimization Variables

4.2.1 Satellite uplinks positions

As we have mentioned earlier, the main variable of the deployment of broadcast satellite links is satellite uplinks positions. Suppose that we have F feeds (uplink satellite stations) to add to the terrestrial network composed with N nodes. There is C_N^F possible configurations of the hybrid network. A configuration is obtained by adding F satellite uplinks in F selected terrestrial network nodes. For example, for $N = 100$ and $F = 10$, we have $1.7 * 10^{13}$ possible configurations. It is so infeasable to explore all solutions in order to find the optimal hybrid topology. Besides, if the processing time of a given topology is equal to $1ms$, it takes 550 years to find the optimal one.

4.2.2 Uplinks capacities

There are several multiple access techniques used to share satellite bandwidth between all feeds. The basic contenders are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA), though some hybrid combinations of these basic technologies are also possible. Capacity comparisons of satellite systems based on these multiple access techniques can be found, for example, in [9] between FDMA and CDMA, and in [2] between CDMA and TDMA.

Regardless of multiple access technique used by the satellite operator, we suppose, in this paper, that we have some discrete capacities which can be offered by the satellite provider. During the optimization process, we should determine all satellite uplinks capacities which optimize the global network state.

4.2.3 Routing policy

Many routing policies have been proposed in the Internet such as fixed, adaptive and hierarchical. In our case, we consider a deterministic routing policy for tow main reasons. The first one is the facility of flow determination in all communication links. The second one is related to the independence assumption of Kleinrock which is verified in the case of deterministic routing protocol and it not realistic when we use an adaptive routing policy [15].

As we have to propose analytic resolution methods, we use static unicast and multicast routing protocols based in the link tunneling mechanism proposed by IETF UDLR working group in [12] in order to support routing in communication networks connected via unidirectional links to a GEO satellite. The use of this mechanism permits to leave upper layer unchangeable by emulating bidirectional connectivity between nodes that are directly connected by a unidirectional link.

4.2.4 Communication channels flows

Links flows are composed of traffic generated by different classes of traffic. Best-effort traffic and guaranteed traffic are generated by unicast as well as multicast applications. The aggregated traffic in a given link depends on routes calculated by routing algorithms and it is expressed in packets/second for best-effort class and in calls/second for guaranteed classes.

For best-effort class and based on the assumption that all packets circulated in the network have the same mean length, the mean number λ_j^{tb} of unicast packets arrived per second to link M_j, is equal to the sum of all traffic γ_{kl}^{tb} using this link. Then,

$$\lambda_j^{tb} = \sum_{1 \leq k,l \leq N,\ j \in \Re_{k,l}} \gamma_{kl}^{tb} \tag{1}$$

with $\Re_{k,l}$ is the route between k and l.

The aggregated unicast traffic λ_j^s in link j for guaranteed class s is expressed in calls/second and it is computed as follow:

$$\lambda_j^s = \sum_{1 \leq k,l \leq N,\ j \in \Re_{k,l}^s} a^s(k,l) * \gamma_{kl}^s \tag{2}$$

where $\Re_{k,l}^s$ is the route between k and l for guaranteed class s and $a^s(k,l)$ is the probability that a call s be admitted in all links in the route between k and l. Of course, this probability is equal to the product of probabilities that each link in the route accepts the call.

For multicast traffic, we interest to the mean multicast traffic generated by multicast group p in all links of the multicast tree of this group. It can be calculated by:

$$\gamma_g = \sum_{i=1}^{i=n_g^s} \gamma_{ig} \tag{3}$$

where n_g^s is the number of sources in the multicast group g and γ_{ig} is the mean number of packets sent by source i to multicast group g.

4.3 Optimization Goals

4.3.1 Network performance

As it is shown in Table 1, performance evaluation metrics of a hybrid network differ according to the studied type of traffic.

While we use an analytic resolution and not a simulation-based resolution, expressions of all performance metrics will be calculated by resolving proposed analytic models. For each type of traffic, we suggest to use an analytic model that describes this traffic and its interaction with other types of traffic.

4.3.2 Network cost

The network cost is the sum of satellite uplinks cost. An uplink satellite cost depends on the capacity allocated to this uplink and the payment policy used by the satellite operator. The cost function is composed with two terms: constant term expressing equipments and setup cost and a variable term giving the cost of the satellite uplink according to its capacity.

We suppose that the function cost D_j of satellite uplink j is linearly increasing with its capacity. Then

$$D_j = \alpha + \beta * C_j \tag{4}$$

where α is the equipments and setup cost and β is oer unit cost of capacity.

As we suppose that we have discrete capacities that can be allocated to each satellite link, D_j has discrete values.

4.4 Optimization Constraints

Like all optimization problems, a number of constraints must be verified during the resolution process. In the case of the resolution of GEO satellite links deployment problems, we face several constraints which are either technological constraints or traffic-imposed constraints. We enumerate in the following sub-sections these different constraints.

4.4.1 Uplinks number constraint

As we have mentioned and considering technology limitations, there is a maximal number of satellite uplinks able to be supported by a satellite using the on-board processing technology. Let us denote by F_{max} the number of feeds and by F the number of satellites feeds in a given hybrid topology. This constraint can be reduced to the simple inequality $F \leq F_{max}$ which should be verified in each iteration of the optimization algorithm.

4.4.2 Flow constraint

The flow conservation condition for each pair of nodes (i,j) is:

$$\sum_{j=1}^{N} f_{ji}^{(k,l)} - \sum_{j=1}^{N} f_{ij}^{(k,l)} = \begin{cases} -\frac{\gamma_{kl}}{\mu} \text{ if } i = k \\ +\frac{\gamma_{kl}}{\mu} \text{ if } i = l \\ 0 \text{ if not} \end{cases} \tag{5}$$

where $f_{ij}^{(k,l)}$ is the flow sent by node i to node j using the link (k,l) for each $1 \leq k,l \leq N$.

4.4.3 Capacity constraints

The first capacity constraint which should be verified by each optimization problem is related to capacity limitation of the satellite uplink. Indeed, the capacity C_j of a satellite link j must be one of the discrete capacities offered by the satellite provider and the sum of uplinks capacities should not exceed the bandwidth of the GEO satellite.

A second capacity constraint which guarantees the feasibility of the solution that the flow generated in each communication link should not exceed its capacity. Then,

$$f_j \leq C_j \text{ for each link } j = 1...M \tag{6}$$

f_j is the total flow traversing the link j and C_j is the capacity of link j. The total flow of link j is given by the following expression:

$$f_j = \alpha_j^{tb}\lambda_j^{tb} + \sum_{s=1}^{s=S} \alpha_j^s \lambda_j^s \tag{7}$$

with:

- λ_j^{tb} (resp. λ_j^s): mean number of best-effort packets (resp. calls belong to guaranteed class s) using the link j expressed in packets/second (in calls/second).
- α_j^{tb}: mean size of packets generated by a best-effort session and using the link j expressed in bits/packet.
- α_j^s: mean size of data generated by a session belongs to guaranteed class s using the link j expressed in bits/session.

When we have to share network resources between all classes of service: guaranteed service and best-effort service, another capacity constraint should be added in order to guarantee that the best-effort class is not completely blocked. It limits the bandwidth consumed by guaranteed classes in each communication link. In others terms, we should verify that:

$$\sum_{s=1}^{s=S} \alpha_j^s \lambda_j^s \leq C_j^{tg} \text{ for each link } j = 1...M \tag{8}$$

with C_j^{tg} is the maximal capacity that can be allocated to guaranteed traffic.

Of course, in the case of best-effort traffic optimization, the capacity constraint is reduced to:

$$\alpha_j^{tb}\lambda_j^{tb} \leq C_j \tag{9}$$

and it will be limited to:

$$\sum_{s=1}^{s=S} \alpha_j^s \lambda_j^s \leq C_j \text{ for each link } j = 1...M \tag{10}$$

in the case of guaranteed traffic optimization.

4.4.4 Cost constraint

The topology obtained should have a total cost D less than the maximal cost D_{max} ($D \leq D_{max}$) where D_{max} is the maximal budget allowed and which is an input of the planning problem. The total cost D is simply the sum of the costs of each satellite uplink. Then,

$$D = \sum_{j=1}^{j=F} D_j \leq D_{max}$$

is the inequality that should be verified in each iteration of GEO links deployment algorithm and F is the number of satellite uplinks (feeds).

4.4.5 Delay constraint

The delay constraint is:

$$T \leq T_{max} \tag{11}$$

with T_{max} is the mean transfer delay that should not be exceeded. This constraint should be verified when the performance metric of the type of traffic is the mean transfer delay. It is the case with best-effort optimization and reliable multicast optimization problems.

4.4.6 Calls blocking probability constraint

Noting by B^s the call blocking probability matrix of guaranteed class s and by B^s_{max} its maximal call blocking probability. The call blocking probability constraint to be considered during the optimization of guaranteed traffic is the following inequality:

$$B^s < B^s_{max} \quad \forall\ 1 \leq s \leq S \tag{12}$$

with S is the number of guaranteed classes.

In others terms:

$$B^s_{i,j} < Bmax^s_{i,j} \text{ with } 1 < i,j < N \text{ and } 1 < s < S \tag{13}$$

5 Optimization Problems

Using terminology and concepts introduced above, we define in this section all optimization problems of the deployment of GEO satellite links in the Internet.

As shown in Figure 3, the main goal of the general planning problem of hybrid multiservices networks is to find the optimal hybrid network topology which satisfy all constraints listed above and which optimize performance metrics of every type of traffic: mean transfer delay for best-effort transfer, call blocking probability for guranteed transfer, mean cost of multicast trees for unreliable multicast transfer and mean transfer delay of reliable multicast packet.

As we can notice, there are many criteria that should be optimized during the resolution of this general optimization problem. The function to minimize is a weighted function of different performance metrics of different types of traffic. Therefore, the goal is to minimize the following function:

$$F = \alpha_1 * \text{DelayBestEffort} + \alpha_2 * \text{MaxBlocProb} \ + \alpha_3 * \text{TreeCost} + \alpha_4 * \text{DelayMulticast} \tag{14}$$

	Inputs	**Variables**	**Goals**	**Constraints**
General Optimization Problem	Terrestrial topology Reliable multicast groups Unreliable multicast groups Network load	Satellite Uplinks Positions Satellite Uplinks Capacities	Mean best-effort transfer delay Guaranteed calls blocking probabilities Mean cost of multicast trees Mean delay of reliable multicast transfer	Uplinks number constraint Capacity constraint Cost constraint Flow constraint Delay constraint Calls blocking constraint
Best-effort Traffic Optimization	Terrestrial topology Best-effort traffic	Satellite Uplinks Positions Satellite Uplinks Capacities	Mean best-effort transfer delay	Uplinks number constraint Capacity constraint Cost constraint Flow constraint Delay constraint
Guaranteed Traffic Optimization	Terrestrial topology Calls matrix Calls requirements	Satellite Uplinks Positions Satellite Uplinks Capacities	Guaranteed calls blocking probabilities	Uplinks number constraint Capacity constraint Cost constraint Flow constraint Calls blocking constraint
Multicast Traffic Optimization	Terrestrial topology Reliable multicast groups Unreliable multicast groups Multicast traffic matrix	Satellite Uplinks Positions Satellite Uplinks Capacities	Mean cost of multicast trees Mean delay of reliable multicast transfer	Uplinks number constraint Capacity constraint Cost constraint Flow constraint Delay constraint

Figure 3: Optimization problems of GEO satellite links deployment

The solution which is used, in general, for the resolution of such optimization problem and that we use, consist to divide the problem to a set of optimization sub-problems which are studied separately, either by exact algorithms or by heuristics. We propose to study three optimization sub-problems:

- Best-effort traffic optimization.
- Guaranteed traffic optimization.
- Multicast traffic optimization.

Every sub-problem is defined in Figure 3 by a set of inputs, variables, goals and constraints.

The mean packet transfer delay is the metric used for best-effort traffic. Then, the optimization goal is to find the hybrid optimal topology offering the minimal mean transfer delay. The problem of best-effort traffic optimization has been studied in several research works and several analytic models have been proposed in [13] and [15] for terrestrial packet switching networks. However, the current tendency in the area of network technology is to offer an end-to-end quality of service and then considering the best-effort traffic separately from guaranteed traffic seems to be a bad solution. Hence, we propose to study the coexistence of best-effort traffic and guaranteed traffic. That's why, to ensure the coexistance of best-effort and guaranteed traffic, we have introduced in Section 4.4.3 constraints of the coexistence of the two different types of traffic in the same communication network. Thus, the problem of best-effort traffic optimization will be reduced to that of guaranteed traffic optimization by taking into account the existence of best-effort traffic.

In order to find a hybrid topology which support efficiently guaranteed service, it will be necessary to minimize calls blocking probability during the optimization process of this type of traffic. During the resolution of this problem, we look to add satellite uplinks in strategic positions in order to minimize calls blocking probability. It needs the elaboration of an analytic model estimating these probabilities and which takes into account the co-existence of guaranteed traffic and best-effort traffic. Many analytic models have been proposed in [22] and [21] and have been used for designing muliservice networks based on ATM technology.

We distinguish between reliable multicast and unreliable multicast considering that the first type needs that all members receive correctly packets sent by the multicast source whereas the second type of transfer may work even with loss packets. The mean cost of multicast trees is the performance metric used for unreliable multicast traffic and as it was indicated earlier, the most significant performance metric of reliable multicast optimization is the mean transfer delay of multicast packet. To resolve this problem, we need to define an analytic model to evaluate the mean transfer delay of a reliable multicast packet. Moreover, it is necessary to define an analytic model which gives the number of retransmissions of a multicast packet sent by the source until it will be correctly received by all members.

The problem of multicast traffic optimization will be detailed in Section 7 and results will be presented.

6 Proposed Optimization Heuristic

After the motivation of the choice of analytic resolution instead of simulation resolution approach, we develop, in this section, the global optimization heuristic that we propose to solve all hybrid network optimization problems. The details of its main steps depend on the type of traffic studied and then on the optimization sub-problem.

6.1 Analytic resolution vs. Simulation resolution

The network planning step is a crucial step in the global network optimization process. There are two main approaches that can be used to evaluate the performance of a communication network. The first one is to estimate its performance metrics values using analytic models and the second one is a simulation-based approach. Discrete event simulation approach is considered as a powerful performance evaluation tool. However, even for small networks, it consumes a lot of processing time in order to find efficient results.

Our proposed hybrid network model integrates several types of traffic which differ by their requirements in network resources and their transfer mode. The use of simulation approach to evaluate their performance seems not to be a good solution. Indeed, simulation time should be large in order to reach a stationary state. That's why we suggest to use the simulation approach only for validating analytic models. This validation can easily done for small hybrid topologies before it will be generalized for more complex and great topologies.

6.2 Heuristic Overview

The general flow chart of the proposed planning algorithm is shown in the Figure 4 where F is the number of satellite uplinks (feeds) in the current hybrid topology. In fact, the algorithm starts by evaluating the performance of the initial terrestrial topology and then it executes two main steps which are[2]:

- ♦ Finding an optimal position where to add the satellite uplink.

[2]Details of these steps depend on the studied type of traffic.

- ♦ Performance evaluation of the current hybrid topology.

The first step consists for looking for the optimal position where we should add the satellite uplink in order to improve the network performance. In the second step and according to several performance criteria, the algorithm acts to evaluate the performance metrics of the new hybrid topology according to the traffic type. The resultant topology will be considered as the optimal temporary topology only if we ensure that our method used to find the optimal position of the satellite uplink is a convergent method. The process stops when the optimal topology is reached or the number of satellite uplinks added is equal to the maximal number.

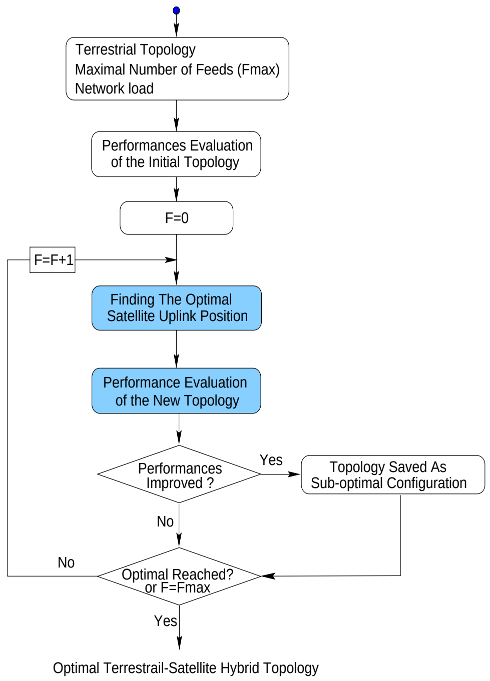

Figure 4: Flow chart of the optimization method

Noting that the general resolution method that we propose is just a heuristic and not an exact algorithm and several modifications should be done when we will examine separately optimization sub-problems. These modifications concern mainly the two crucial steps.

6.3 Performance Evaluation Step

The step of performance evaluation of current topology is the more critical and complicated step. It is critical considering that after this step we decide if the topology is the optimal one or not and it is complicated because the studied network is not only a hybrid network with different constraints but also a multiservice network which makes the evaluation step more hard to achieve.

The optimization goal which we consider in our study is the improvement of performance metrics that we have detailed in Section 3 and the network cost which is a function of satellite uplinks capacities. For each type of traffic there is one or more performance metrics whose expressions are deduced after the resolution of the analytic model.

6.4 Satellite Uplink Addition Step

After evaluating performance of the current hybrid topology during an iteration of the algorithm of Figure 4, we should add a new satellite uplink. Suppose that we have f satellite uplinks and n possible nodes where we can add these uplinks. The number of possible configurations is then C_n^f.

The immediate solution for finding the optimal position of the satellie station is to study all possibilities and then to determine the optimal position of the new satellite uplink to add. Of course, this position is which optmizes the goal of the optimization problem. As we have mentioned in Section 4.2.1, it is very expensive in processing time to find the optimal topology by the examination of all possibilities. A solution which is more efficient consists of finding the optimal position that optimizes the studied types of traffic without processing all possibilities using a specific method which depends on class of service and mode of transfer of the studied traffic.

7 Case Study: Multicast Traffic Optimization

In this section, we detail the problem of GEO satellite links deployment in order to optimize the use of multicast applications. The goal is to determine strategic positions of satellite uplinks which improve multicast traffic performance criteria.

In the following sections, we explain in details the two main steps of the optimization process.

7.1 Optimal Uplink Position

We can always imagine several techniques that we can use to determine the position where to add the satellite uplink. Indeed, this position can be in one of sources of the multicast group having the more costly multicast tree, in a multicast source belongs to many multicast groups or in the nearest node to multicast sources of all groups and which may be not a member of each group.

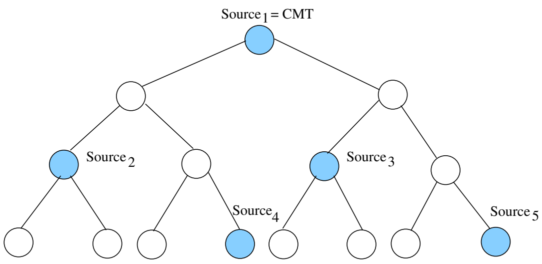

Figure 5: Selection of CMT of a multicast group

It is evident that each technique listed above minimizes the mean cost of the multicast trees since multicast routing protocols will take into account the presence of the new satellite communication uplink when building multicast trees (Section 7.4 gives a comparative study). In the worst case, we will obtain the same mean cost of multicast trees even after adding a satellite uplink in the selected position. However, the main drawback of all these methods is that they do not consider the performance metric when they determine the satellite uplink position therefore we are not sure that the selected position is the optimal one and that we can not find another position that gives best performance metrics values. That's why we propose a more sophisticated method which is not only a metric-based algorithm but also guarantees the *fairness* between all multicast groups.

For each multicast group, we determine a particular multicast source that we called CMT (*Center of Multicast Tree*). The CMT is a multicast source among the sources of the same multicast group (see Figure 5). The CMT_g of group g will be that source which is closest to all other multicast sources. 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.

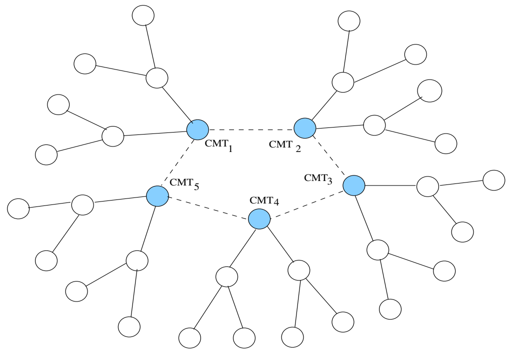

Figure 6: Arrangement of different CMTs

After determining the CMT List for each multicast group, the next step is to select the optimal position among the CMTs of all multicast groups. We should arrange the CMT matrix in order to determine in each iteration the optimal CMT in which we will add the satellite uplink. In order to guarantee the fairness between all multicast groups, we propose an arrangement by column since we treat separately CMT Matrix columns. For each column, we consider the multicast group composed by nodes of this column and we change it by the CMT List of this group (see Figure 6). As result, we will have an arranged CMT Matrix that 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 optimal one for the current iteration of the optimization method of the multicast transfer.

Since we examine the CMT matrix column by column, a multicast group can not have two satellite uplinks while another group do not have a multicast source that is a feed therefore the *fairness* between multicast groups will be guaranteed.

7.2 Performance Evaluation

7.2.1 Unreliable multicast transfer

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

7.2.2 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:

$$T_{trans} = t_r + t_r * \overline{R(G)} \tag{15}$$

and the propagation delay is:

$$T_{pro} = RTT_m + RTT_m * \overline{R(G)} \tag{16}$$

where RTT_m is the maximal RTT (*Round Trip Time*) between source and receivers. We define the RTT as the propagation delay on the path from the source to the receiver. Using (15) and (16), we obtain the expression of mean transfer delay of a reliable multicast in a hybrid network as follows:

$$T = T_{trans} + T_{pro} = t_r + RTT_m + (t_r + RTT_m) * \overline{R(G)} \tag{17}$$

Biersack and Nonenmacher have given in [20] 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:

$$\overline{R(G)} \simeq PL \tag{18}$$

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 (17).

7.3 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 [28] and PIM-DM [8] periodically flood data packets throughout the network. MOSPF [19] floods group membership information to all the routers so that can build multicast distribution trees. Protocols like CBT [5] and PIM-SM [4] 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 [7].

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 directely 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.

7.3.1 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 [4]. Routers belonging to the set of Candidate-BSRs or Candidate-RPs should be manually configured in the network [4]. For hybrid networks, we assume that all CMTs are configured as Candidate-BSRs and Candidate-RPs[3] (see Section 7.1 for more details about how we compute the CMT Matrix).

[3] [4] recommends that C-BSRs should be equal to C-RPs.

In order to profit from satellite link broadcast nature, the RP placement policy that we recommend in such type of network depends on satellite uplinks (feeds) positions 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.

This policy of RP placement in a hybrid network can be satisfied by effectively choose the priority value of each RP in the Candidate-RP message sent to the BSR.

7.3.2 Switching from a RP-routed tree to a SPT

PIM-SM specification [4] 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 a terrestrial-satellite 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 for that particular source), or if the RP has already joined the (S,G) tree and it receiving the data packets natively. Then we recommend that all satellite receivers members join directely the source. This can be done by properly configured the threeshold maintained by the router. For example, we can attribute for each (S,G) a threeshold 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 [12]. The threeshold maintained by each member for the (S,G) entry should be then greater.

A major advantage of PIM-SM used in hybrid networks is the option provides routers to switch from an RP-shared tree to a Shortest-Path-Tree (SPT) as soon as they start receiving data packets from the source.

PIM-SM, used with UDLR, grants an efficient use of communication links resources considering that multicast packets will be sent via the satellite downlink. Terrestrial links will then be used effectively by applications that need resources that cannot be offered by the satellite connectivity.

7.4 Optimization results

We performed simulations to study the quality of multicast transfer in hybrid network and to analyze results obtained by the satellite uplinks positions selection method that we have proposed in Section 7.1.

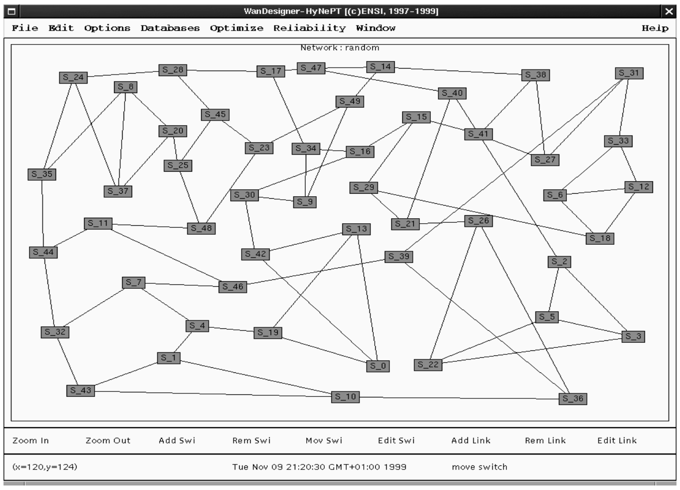

Figure 7: Terrestrial generated topology

The terrestrial topology was been 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 chosen randomly (see Figure 7). The size of each multicast group was generated randomly between 1 to the network size. We compute, using PIM-SM (see Section 7.3), per multicast group and per source the multicast delivery tree which can be a RP-routed tree or a source-based tree. This tree contains only active terrestrial and satellite branches.

We begin by demonstrating the importance an effective choice of the positions of satellite uplinks in the terrestrial network. We compare results obtained for two satellite uplink position selection methods: (1) postions chosen randomly and (2) positions determined using our method described in Section 7.1. We show in Figure 8, the mean cost of multicast trees vs the number of satellite uplinks added obtainted by each method.

It is clear from the plots of Figure 8 that both methods improve the mean cost of multicast trees, but improvement offered by an efficient selection of satellite uplinks decreases more the mean cost of multicast trees.

Figure 9 shows the variation of the mean cost of multicast trees in function of the number of satellite uplinks for three different cases: 10 groups, 20 groups, and 30 groups.

In the optimization process, we add in each iteration a new satellite uplink until we reach the optimal configuration. This configuration is obtained when the addition of a new satellite uplink does not decrease the multicast tree mean cost. This case will be realized when the number of feeds reach the maximal number ($F_{max} = 20$) or when the number of nodes which are multicast sources is less than F_{max} since satellite uplinks will be placed only in multicast sources. In our example, the number of different multicast sources is equal to 27 which equal to different CMTs in the CMT matrix.

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 7.3). Also, we notice that the mean cost of multicast trees increases with the number of multicast groups. Indeed, the mean cost of multicast trees in the case of 30 groups is greater than that

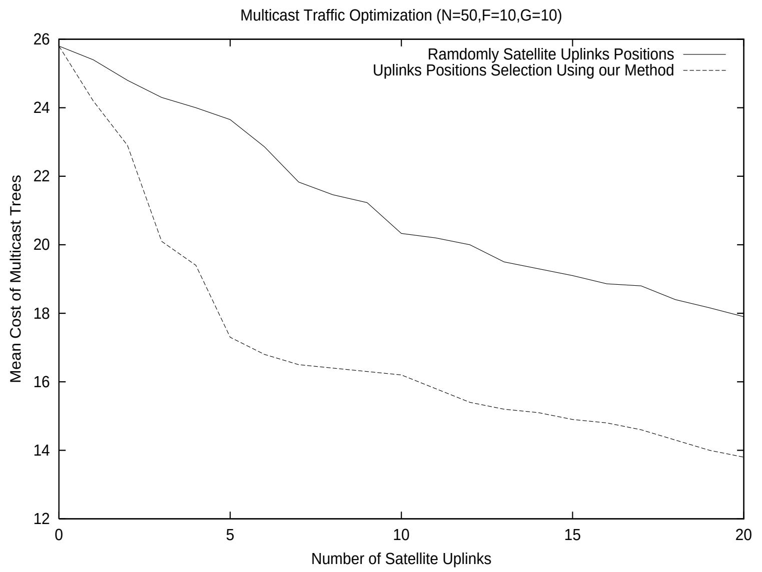

Figure 8: Comparison of two methods of satellite uplink position selection

of 20 groups which is greater than the case of 10 groups. These inequalities remain verified even after the addition of satellite uplinks in the terrestrial network.

The improvement of the mean cost of multicast trees is more remarkable during the addition of the first satellite uplinks and this improvement decreases in function of number of satellite uplinks added to the terrestrial network.

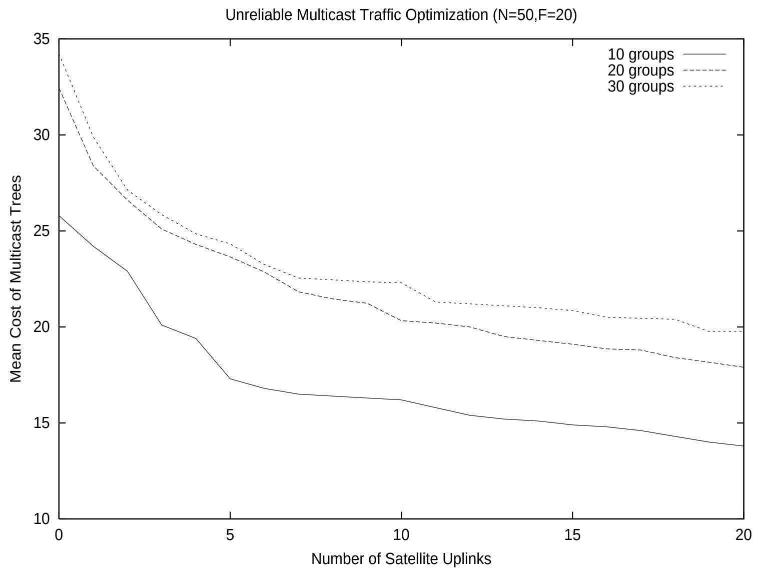

Figure 9: Unreliable multicast traffic optimization

We plotted in Figure10 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 link. A loss probability of 0.001 and 0.03 was assumed for satellite and terrestrial links respectively, representative of losses on the MBONE [23]. The satellite delay was assumed to be 250 ms.

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.

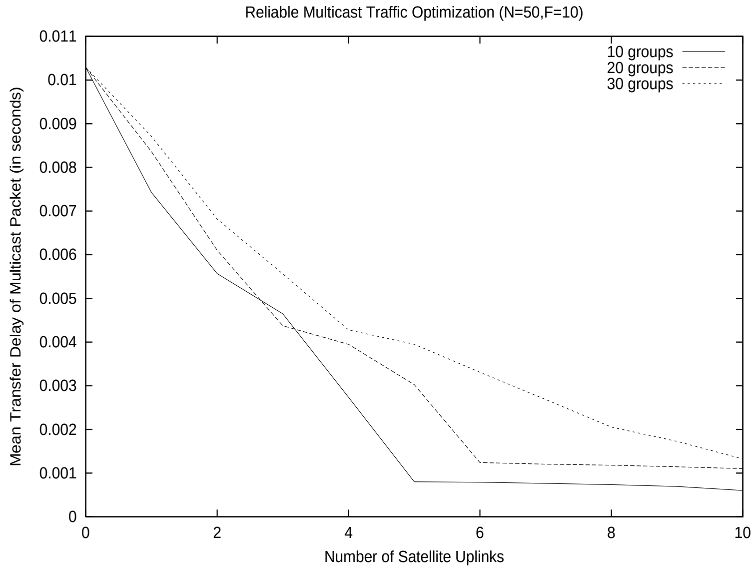

Figure 10: Reliable multicast traffic optimization

Curves of Figure 9 and Figure 10 allow us to determine how many satellite uplink stations we should add in order to reach a given mean cost of multicast trees and/or a given multicast mean transfer delay. As result of the optimization algorithm, we obtain also positions of satellite uplinks.

8 Conclusion

In this work, we have introduced the problem of GEO satellite links deployment in the Internet. 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.

A resolution heuristic was been proposed which contains essentially two main steps depending on the studied type of traffic. The first one is the performance evaluation step in which we try to find values of current hybrid network performance metrics and the second one interest to find a new position of a GEO satellite uplink to add in order to improve these metrics.

By the end of this paper, we have studied in details the problem of multicast transfer optimization. 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 correctely choose where to add satellite uplinks by considering positons of multicast sources.

Further works will be investigated in order to study other types of traffic that we have presented in Section 5 and to combine the optimization methods and then to propose a general optimization method.

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