Satellite-HAP Network Supporting Multilayered QoS Routing in the Sky

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ABSTRACT
The main features of the future mobile communication systems are the provisioning of high-speed data transmissions (up to 1 Gb/s) and interactive multimedia services. For effective delivery of these services, the network must satisfy some strict quality-of-service (QoS) metrics, defined typically in terms of maximum delay and/or minimum throughput performances. According to this general vision, the integration of different layered networks play one of the most important roles in the telecommunication systems; for this reason, the paper explains the potential role of an integrated satellite-high-altitude platform (HAP) terrestrial system proposing a new multilayered inter-HAP-satellite routing (IHSR) algorithm integrated with an efficient admission control scheme in order to guarantee an adequate QoS to multimedia traffic connections. The performance of the overall architecture is evaluated through intensive simulations comparing the proposed algorithm with a previous classical routing scheme under several traffic load scenarios and network dimensions. The obtained results demonstrate the goodness of the proposed strategy in terms of handled active connections and inter-HAP link utilization.

Keywords: Connection admission control, High-altitude platform, Multimedia, Routing, Satellite, QoS.

1. INTRODUCTION
Network operators and service providers are experiencing the increasing demand of remote users for broadband access to internet services. In order to meet this demand, the use of satellites is essential to complement terrestrial systems and extend their coverage beyond densely populated areas, providing a broadband “internet-in-the-sky” infrastructure.

Wireless solutions provide personal communications to mobile and fixed users and may solve the “last mile” problem, i.e., the direct service delivery to customers’ premises, offering high-bandwidth services without relying on a fixed infrastructure. Furthermore, in many scenarios wireless represents the only viable delivery mechanism. A potential solution to the wireless delivery problem lies with aerial platforms, capable of carrying communication relay payloads and operating in a quasistationary position at altitudes up to 22 km. High-altitude platforms (HAPs) can offer a wide range of services. These include rural telephony, broadcasting, and data services. Such services may be particularly valuable where existing ground infrastructure is missing or difficult. Moreover, HAPs are ideally suited to the provision of centralized adaptable resources allocation, i.e., flexible and responsive frequency reuse patterns and packet sizes, unconstrained by the physical location of base stations. Such almost real-time adaptation should provide greatly increased overall capacity compared with current fixed terrestrial schemes or satellite systems [1,2]. In particular, such platforms could effectively integrate or substitute terrestrial satellite systems in different ways: as an example, they can be rapidly deployed to provide immediate coverage in disaster areas, or relocated, expanded, and upgraded with new payloads, reducing the obsolescence risk typical for traditional satellites.

According to the previous vision, the new communication systems architectures will be multilayered architectures in which the design of an efficient routing strategy through the different layers will be the most important research issue in order to offer a high quality-of-service (QoS) level to the network users.

One of the challenges of HAP-satellite networks is the development of specialized routing algorithms. The routing algorithms for multilayered networks should compute paths with low communication and computational overhead, and adapt the routing decisions to the network topology and the network status in real time.

The paper investigates issues related to the optimal routing and admission control strategy in a multilayered terrestrial-HAP-satellite network; a novel routing strategy for this system architecture is proposed highlighting the strengths and evaluating the performances through an intensive simulation analysis. Furthermore, the
simulation analysis has been extended to different network topologies in order to investigate the robustness and scalability of the proposed solution.

The paper is organized as follows. Section 2 summarizes few works conducted in the past years and are related to the topic presented in this paper. Section 3 presents the network system architecture. Section 4 describes some signaling and connection admission control (CAC) issues. Section 5 illustrates the routing problem and shows the inter-HAP-satellite routing (IHSR) algorithm formulating the optimal routing problem on the HAP and satellite layers. Section 6 gives the results of the simulation campaigns discussing the goodness of the proposed approach under several traffic conditions and network dimensions in terms of nodes amount; finally, conclusions and future research issues are summarized in section 7.

2. RELATED WORKS AND THE LITERATURE

A lot of studies have been conducted in the recent years on the low earth orbit (LEO) satellite networks focusing on the connection-oriented routing issue; the heuristic routing algorithm proposed in [3] aims to reduce the number of path handovers due to the satellite mobility. The algorithm presented in [4] uses the snapshots of the constellation to optimize the paths. A QoS-based LEO satellite network is described in [5], which includes a routing scheme that resembles minimum hop routing in Manhattan street networks [6]. In [7], a two-layered satellite network architecture consisting of LEO and medium earth orbit (MEO) satellite networks and a routing algorithm are proposed.

Others recent research activities have placed much emphasis on various online and offline routing algorithms well suited only for the satellite segment assuming a well-known link capacity [8-10].

The multilayered architecture tested in this work has been shown in [11] in order to better clarify the potential role of an integrated satellite-HAP-terrestrial cellular system; it has been designed within the SHINES project [12].

Although this integrated multilayered architecture is really new, few studies about the desirable integration of terrestrial, HAP, and satellite layers have been conducted in the last 2 years. In [13] Cianca et al. presented two integrated HAP-satellite scenarios, in which the HAP is used to overcome some of the shortcomings of satellite-based communications also providing more efficient fleet-management and traffic-control services and more powerful data-relay systems. In [14] the authors discuss different hybrid system architectures with an emphasis on the merits of HAPs and provide a potential mapping of services to the components of a terrestrial-HAP-satellite integrated system. In [15] Alloci et al. considered an integrated HAP-satellite architecture and proposed a reliable multicast protocol that capitalizes upon the HAP layer to perform local retransmissions. However, the presented analysis does not take into account the issues related to the optimal routing within the multilayered network architecture. For addressing this issue, the lessons learnt by the works performed on the LEO system are still valid and can be used as a starting point for the design of an ad hoc HAP-satellite routing algorithm, especially thanks to the advent of high-speed space optical crosslink [16]. Moreover, the advent of hierarchical architectures implies more redundancy and routing choices; thus, a variety of topological design and routing issues should be investigated to enable the best use of satellite technologies in the future communication systems.

3. SYSTEM ARCHITECTURE OVERVIEW

The system architecture studied and tested in this work is shown in Figure 1; return channel communication is only via HAP whilst forward channel communication can happen both through satellite and HAP links. Terminals should be able to work on different frequency bands in order to receive communications on a forward link both from satellites and HAPs. This system consists of three layers: terrestrial layer, HAP layer, and GEO layer.

Terrestrial layer is composed of all user terminals, management, and control stations including satellite master control station (S-MCS) responsible for the overall system supervisioning. Terminals can be classified according to their mobility, sizes, functions, and transmission rates. Both HAP-gateway (H-GTW)
and HAP-master control station (H-MCS) terrestrial terminals must exist for each HAP coverage area; for simplicity, we assume that H-MCS is a module within the H-GTW as shown in Figure 2.

We choose to use terminals based on the DVB-RCS standard [17] named RCHT (return channel HAP terminal). The DVB-RCS standard is based on the use of the already existing DVB-S standard in the forward link. DVB-RCS and DVB-S are used in return (ground-to-HAP-satellite) and forward (satellite-to-HAP-ground) links, respectively. Since the DVB-RCS standard defines two types of traffic bursts carrying either ATM cells or MPEG2-TS (moving picture expert group 2-transport stream) packets, we decide carrying IP packets via DVB/MPEG2-TS (188 byte) in the return and forward directions.

Due to the different user profiles, a distinction of the RCHTs based on the transmission rate is necessary. The following four different typologies of RCHTs, having different bandwidth capacity and belonging to different user profiles, are considered and tested in the system: RCHT A for a consumer market (return link ≤144 kbit/s), RCHT B for a professional/consumer market (return link ≤384 kbit/s), RCHT C for a professional market (return channel ≤1024 kbit/s), and RCHT D, corporate oriented (return channel 2048 kbit/s).

The forward link capacity is fixed to 64 Mbit/s and a MF-TDMA scheme is chosen in the return direction with a bandwidth capacity of 32 Mbit/s for each coverage area.

The stratospheric platform layer hosts the set of HAPs that carry out routing, switching, and traffic management. In this scenario, besides the bidirectional communication with the terrestrial layer, it also exists as a bidirectional interface with the GEO layer. Inter-HAP links (IHLs) are provided in order to increase system flexibility also improve path routing optimization.

The satellite layer uses GEO regenerative satellites that are provided with on-board processing (OBP). It can use the forward channel both toward the terrestrial layer and the HAP layer.

4. SIGNALLING ISSUES AND CAC ALGORITHM

In this work, a link-state routing strategy is assumed. The adopted link-state approach is performed by every node in the network. The basic concept of link-state routing is that every node owns a map of the network connections and inspecting this map each node calculates by itself the best next hop from it toward every possible destination in the network.

Each node gets its own map using link-state advertisements periodically sent through the network.

The map of network connections can be designed as a graph in which satellites, HAPs, and user terminals are the nodes, radio links between nodes represent the edges, and a sequence of links between a source node and a destination node is a path.

We considered that routing decisions are taken by H-MCS and S-MCS. Both HAPs and satellites implement only switching functions so they receive and forward commands from/to H-MCS and S-MCS.

When a source terminal wants to establish a connection with a destination terminal, it sends a connection request message (CRM) to its H-MCS of origin using HAP coverage; after that, H-MCS computes the best path. If source and destination terminals belong to the same coverage area (CA) an inner path within the coverage area is explored otherwise an outer path is calculated.

Once the best path is chosen, an admission phase is performed. During this phase, a CAC procedure tries to reserve resources for all involved links.

The CAC algorithm, designed for handling multimedia traffic in a DVB-RCS satellite system and tested in previous works [18,19], runs in the H-MCS and S-MCS in order to guarantee a flexible bandwidth allocation, avoiding the a priori partitioning of the resources among different types of service.

The admission algorithm [19] presents a very low (linear) computational complexity because it is founded on a few elementary sum, subtraction, and product operations. Moreover, it is very flexible to any changes in the service management policy because it is based on a small set of configurable source parameters like MDR (mean

Figure 2: Communication between terminals placed in the same coverage area (CA).
data rate), standard deviation, and the BEF (band-width expansion factor) that represents the QoS desired by the multimedia connections in terms of GOP (group of picture) loss.

Obviously for an inner path, the admission phase is very simple and fast because it is performed by the HAP, afferent to the area in which the connection has been generated and the communication is handled through the related HAP as shown in Figure 2. The H-MCS runs the CAC procedure for each link in both forward and return directions. If the admission algorithm fails, at least for one link, the connection is refused.

When an outer path occurs a reservation request message (RRM) will be forwarded, through IHLs, from the originating H-MCS to the other H-MCSs belonging to the best path. Upon the reception of the RRM, each H-MCS will try to reserve resources for its own links involved in the path. An outcome message will be sent back to the originating H-MCS. Also in this case, if the admission algorithm fails, at least for one link, the connection request will be refused.

5. THE ROUTING PROBLEM

On-board processing capabilities on HAP allow to have IHLs [20] opening new issues about routing matters; thus the implementation of a suitable decision strategy in order to choose the best path for resource allocation between two different terminals, joined to an efficient hierarchical routing algorithm using HAP and GEO layers, represents a very hot and interesting topic.

The optimal communication path is chosen assigning a different weight value to the following parameters:
- available link capacity
- number of hops to find the destination
- end-to-end delay according to the connection constraints in terms of max-delay and max-packet delay variation (max_PDV)

The proposed routing algorithm called inter-HAP-satellite routing finds a min-hop path with the minimum max usage link cost. Basically, the algorithm finds a candidate set of all min-hop paths, through the IHLs or satellite links, for a given pair of source and destination connections; after that, it chooses the path which is least congested.

5.1 Global HAP Layer Routing Optimization

The optimal routing problem on the HAP layer can be formulated using a LP (linear programming) approach trying to maximize the available capacity of each network link. The variables and constants used in the optimization problem are

\[ \begin{align*}
N &= \text{number of HAPs} \\
N_i &= \text{maximum number of links for the } i\text{th HAP} \\
B &= \text{HAP link capacity} \\
T_i &= \text{offered traffic requirement from HAP } i \text{ to HAP } j \\
U_{ij} &= \text{link connectivity between HAP } i \text{ and HAP } j \\
X_{ijn} &= \text{traffic of link } (i, j) \text{ due to source-destination pair } (m, n) \\
f_{ij} &= \text{total traffic of link between HAP } i \text{ and HAP } j.
\end{align*} \]

The global optimization problem is formulated as follows:

\[
\begin{align*}
\min & \quad z \\
\text{subject to} & \quad z = \max_{i,j} \left( \frac{f_{ij}}{B} \right) \\
& \quad \sum_{j} U_{ij} \leq N_i \quad \forall i \\
& \quad U_{ij} \leq U_{ij} \quad \forall i, j \\
& \quad f_{ij} = \sum_{m,n} X_{ijn} \quad \forall i, j \\
& \quad f_{ij} \leq B \ U_{ij} \quad \forall i, j \\
& \quad \sum_{j} X_{ijn} - \sum_{j} X_{mnj} = \begin{cases} 
T_{mn} & \text{if } i = m \\
-T_{mn} & \text{if } i = n \\
0 & \text{otherwise} 
\end{cases} \quad \forall i, m, n \\
& \quad X_{ijn} \geq 0 \quad \forall i, j, m, n \\
& \quad U_{ij} \in \{0,1\} \quad \forall i, j.
\end{align*}
\]

Here, Equation (2) means that the number of connected links at any node should be equal to or smaller than the total number of IHLS a node can have. We assume that if a link from node \( i \) to node \( j \) is established, then the backward link from node \( j \) to node \( i \) is also established. This is expressed in Equation (3). Equation (4) is the total sum of all traffics on a link \( (i, j) \). The link capacity constraint, Equation (5), specifies that, for each link, the total link traffic should not exceed link capacity \( C \), and if the link does not exist, say \( U_{ij} = 0 \), then this condition enforces that the total traffic along the link should be 0. The traffic conservation constraint (6) specifies that for each source-destination pair \( (m, n) \), which is also called a commodity from node \( m \) to node \( n \), the traffic into a node balances the traffic out of the node. It means that if a node is the source of a commodity, then the outgoing
traffic subtracted from the incoming traffic should be equal to the traffic requirement of the commodity. And inversely, if a node is the destination, the incoming traffic should exceed the outgoing traffic only by the traffic requirement of the commodity. Thus the topology design problem is formulated as a mixed integer optimization problem with a min–max objective function subject to a set of linear constraints. It is practically impossible to solve the problem formulated in this way since this kind of a mixed integer linear programming is known to be NP hard problem and the computation time increases exponentially as the number of nodes increases.

In the next section, we propose a heuristic approach that solves the linear programming problem by decomposing it into two different problems: the first consisting in the paths assignment from a source to a destination and the second consisting in the application of connection admission algorithm to the selected paths.

### 5.2 IHSR Algorithm

The proposed approach is based on two observations:
- The regularity of the HAPs constellation topology
- The most congested IHL belong to a path determined by the hot-link of the path

The hot-link of a path is the most congested IHL in the path, or in other words, the IHL which has the maximum usage value. In the IHSR algorithm, we use the max-usage of a path as a cost model in order to capture the usage cost of the hot-link. First of all, the routing procedure finds the set of min-hop paths (shortest paths, SP) between the source and destination connections verifying that the path’s end-to-end delay is lower than the satellite link delay. If the previous condition is verified, the routing procedure will find the max-usage cost for every path in the set, and then it will compare their cost and it will select the path with the minimum max-usage cost in order to not use the most congested hot-link.

If there is no such path available (e.g., the paths in SP are all congested) or the path delay is higher than the satellite link delay, the new connection is not admitted over the IHL links and the admission control procedure will be performed over the return and forward links of the satellite layer relaxing the constraint on the minimum end-to-end delay.

In a more detailed way, the proposed routing strategy consists of three steps:
- **Uplink routing**: identification of sender HAP for serving the source terminal
- **Downlink routing**: identification of receiving HAP for serving the destination terminal
- **IHL routing**: choice of the best path between the sender and the receiving HAP

The routing problem can be defined as an optimization problem minimizing the maximum link usage and obtaining a network load balance.

In order to better clarify the routing problem formulation, the following definitions need to be explained:

**Definition 1**: $P$ is the set of IHLs belonging to a generic path between two HAPs.

**Definition 2**: $P_{s-d}$ represents the path $P$ from the source HAP $S$ to the destination HAP $D$.

**Definition 3**: $C_{i} = \frac{1}{\text{vacancy}(i)}$ represents the cost of each IHL where the vacancy parameter corresponds to the vacancy number of available channels over the Ith link.

**Definition 4**: $C(P_{s-d}) = \sum_{i \in P_{s-d}} C_{i}$ where $C(P)$ means the cost of path $P$ that is the sum of all the link costs belonging to path $P$.

**Definition 5**: The minimum cost path between the source and destination HAPs, $\min C(P_{s-d})$, is defined to be path $P_{s-d}$ belonging to the set of all possible paths $P_{s-d}$ that has the minimum cost.

**Definition 6**: The end-to-end delay suffered by each packet exchanged between terrestrial terminals through the HAP layer is the following:

$$\Delta T(P) = T_{BIL} + T_{PROC} + T_{QUE} + T_{UP} + T_{DOWN}$$

where

- $T_{BIL} = \sum_{i \in P} L_{\text{IHL}}(i) / \lambda$ is the propagation delay through each IHL belonging to the path where $L_{\text{IHL}}(i)$ is the $i$th link’s length and the term $\lambda$ is the light speed;
- $T_{PROC} = \sum_{i \in P} T_{\text{prox}}(i)$ is the whole processing packet delay throughout the path where $T_{\text{prox}}(i)$ is the time due to the on-board processing for the $i$th HAP belonging to the path;
- $T_{QUE} = \sum_{i \in P} T_{\text{queue}}(i)$ is the whole traffic resource scheduling delay all over the path where $T_{\text{queue}}(i)$ is the time due to the traffic resource manager (TRM) scheduling for the $i$th HAP belonging to the path; $T_{UP}$ and $T_{DOWN}$ represent, respectively, the propagation delay over the HAP return and forward channels.

**Definition 7**: The $Sat_{\text{Delay}}$ is the end-to-end delay suffered by each packet exchanged between terrestrial terminals.
through the satellite layer: it includes propagation, processing, and queuing delays.

Using previous notations, the formulation of the IHSR algorithm from a source $S$ to a destination $D$ is the following:

$$\begin{align*}
\min & \quad z \\
\text{subject to} & \quad z = C \{ P_{s\rightarrow d} \}
\end{align*}$$

$$\Delta t_{\text{EN}} - t_{\text{EN}}(P_{s\rightarrow d}) < Sat_{\text{delay}} \quad (10)$$

This problem formulation is motivated observing that the HAP constellation topology should not have any critical bottleneck link that limits the overall performance; additionally, to minimize the maximum link usage, the algorithm guarantees that the traffic over each link should be distributed as fairly as possible.

Even if the computational complexity of the IHSR algorithm is equal to Dijkstra’s algorithm that is $O(n^2)$ where $n$ represents the number of aerial platforms belonging to the constellation, the selected path using the IHSR algorithm is quite different. A simple example that shows the routing algorithm behavior is given in Figure 3. In the example, we assume that the weight on the graph’s arcs means the number of channel links that are already used; moreover, the maximum link capacity is supposed to be equal to five channels; node 1 is the source node whilst node 6 is the destination node.

Using Dijkstra’s algorithm, nodes $\{1, 2, 3, 6\}$ would have to belong to the minimum path $P_{1\rightarrow d}$ with minimum cost; in this way the algorithm would have chosen a path with a bottleneck on the link between node 2 and node 3. Changing the cost function on the graph’s arcs as already explained and using the IFRS algorithm, the selected path $P_{1\rightarrow d}$ will belong to the nodes $\{1, 4, 5, 6\}$. This new path does not satisfy the Dijkstra conditions about the minimum cost but it satisfies the “max-usage link” condition forced by the IHSR algorithm, balancing the whole traffic load over the HAP constellation.

6. SIMULATION CAMPAIGN AND NUMERICAL RESULTS

In this section, we highlight strengths and weaknesses of the proposed approach and we demonstrate that by combining the routing algorithm with the admission control strategy, it is possible to satisfy the agreed QoS for multimedia connections also providing an elevated level of connectivity and network throughput.

The simulated network topology is based on a HAP constellation with 12 platforms and 1 GEO satellite that provides the whole coverage through the forward link [Figure 11].

We chose a set of real-time multimedia video streaming traffic sources with the aim of testing the system, the designed connection admission control algorithm, and the routing algorithm in a realistic way. In this paper, we choose to show only results for rate-based dynamic capacity (RBDC) [19] traffic service class connections because they are hardest to manage due to the real-time constraints. Different video sources were taken from films such as The Gladiator and Mission Impossible 2. The compression coding technique adopted is the MPEG-2 with a high interactivity level and different mean GOP (group of pictures) data rate ($\mu$) and standard deviation ($o$) values [19].

According to the RCHT bandwidth, we have chosen to use the maximum pixel resolution of 352 $\times$ 288 pixels for traffic sources having a mean data rate equal to 1000 kB/s. This resolution is particularly recommended for MPEG-2 compression on DVB networks carrying SDTV (standard-definition television) applications [21]. For traffic sources with a lower mean data rate (500 kB/s),

![Figure 3: Selected path using Dijkstra (left) or IHSR (right) algorithm.](image-url)
The maximum packet loss probability supportable by real-time connections is fixed equal to 10^{-2} in the whole paper according to [23]; obviously this value is very much higher than the value normally considered in video error resilience work [24], but is potentially very realistic and important in wireless applications where the error rate on the radio channel is considerably higher than wired networks.

In order to accommodate a whole MPEG-2 packet in each slot, the needed atomic channel user rate is fixed to 32 kbit/s [25]. The maximum peak-to-peak packet delay variation value has been chosen equal to the lowest value (one frame) in order to make a worst case analysis. System performances are evaluated according to the traffic scenarios defined in Table 1, also varying the percentage of “inner” connections. An inner connection is a connection between terminals belonging to the same HAP’s hot-spot and, in contrast, an “outer” connection is originated and addressed to terminals belonging to different HAP’s hot-spots. Other key parameters used during the simulation campaigns are summarized in Table 2.

### 6.1 Simulation Approach

The Batch Means [26] method is used for interval estimation in steady-state simulation; this method is based on one long run (versus numerous shorter ones) in which data needs to be deleted only once.

The raw output data is placed in a few large batches, and the analyst works with these few batch means as if they were independent. For our simulations, we chose one long run of 8000 min and 8 batches according to Law [27] who demonstrated how, for a fixed total sample size, it was best to use a very small number of batches of

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Sources composition</th>
<th>Mean data rate (kB/s)</th>
<th>Standard deviation (kB/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100% RBDC</td>
<td>500</td>
<td>32</td>
</tr>
<tr>
<td>B</td>
<td>100% RBDC</td>
<td>1000</td>
<td>64</td>
</tr>
<tr>
<td>C</td>
<td>50% scenario A – 50% scenario B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2: Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCHT typology</td>
<td>D</td>
</tr>
<tr>
<td>Mean connections duration</td>
<td>10 min</td>
</tr>
<tr>
<td>Traffic service class</td>
<td>RBDC</td>
</tr>
<tr>
<td>Return channel satellite</td>
<td>2000 slots – (64 Mb/s)</td>
</tr>
<tr>
<td>Forward channel satellite</td>
<td>4000 slots – (128 Mb/s)</td>
</tr>
<tr>
<td>Return channel HAP</td>
<td>1090 slots – (34.8 Mb/s)</td>
</tr>
<tr>
<td>Forward channel HAP</td>
<td>2000 slots – (64 Mb/s)</td>
</tr>
<tr>
<td>IHL channel dimension</td>
<td>3000 slots – (96 Mb/s)</td>
</tr>
<tr>
<td>Slot dimension (rate)</td>
<td>32 kB/s</td>
</tr>
<tr>
<td>Maximum packet loss ratio</td>
<td>1%</td>
</tr>
<tr>
<td>Frame duration over return and forward channels</td>
<td>47 ms</td>
</tr>
<tr>
<td>Max peak-to-peak packet delay variation</td>
<td>47 ms (1 frame)</td>
</tr>
<tr>
<td>IHL delay propagation</td>
<td>2 ms</td>
</tr>
<tr>
<td>Delay propagation satellite + on-board processing</td>
<td>135 ms</td>
</tr>
<tr>
<td>Normalized traffic load</td>
<td>1</td>
</tr>
<tr>
<td>Percentage of inner connections</td>
<td>0%–10%–20%–30%–40%–50%–60%–70%–80%–90%–100%</td>
</tr>
</tbody>
</table>
longest possible length.

In our simulations the confidence interval level is fixed to 0.95 and the first batch is excluded by the statistical error computation in order to reduce the effects of the system transitory.

6.2 Testing the Routing Algorithm

The simulation campaign is focused on performance evaluation of the whole telecommunication architecture with a particular attention to the proposed routing algorithm behavior compared to a static routing algorithm called MH (minimum hop) that is a special case of the shortest path, in which all links have unitary costs [28].

The MH algorithm is implemented through the well-known Dijkstra strategy in order to find the minimum path between a source and a destination node always using a unit cost value on the links of the HAP constellation. The following figures show the comparison between the two algorithms. Using the IHSR algorithm, as shown in Figure 5, the throughput over the IHLs is about 15% higher when all the connections are addressed out of the HAP coverage area; this behavior is due to an elevated IHL connection blocking probability of the MH algorithm. The throughput gain decreases when inner connections raise and the behavior of the two approaches is quite similar when outer connections are less than 60%. In the latter condition, the throughput over the IHLs is very low making reasonable the use of a static routing algorithm such as MH.

The blocking probability over the IHLs decreases when the number of inner connections increases [Figure 6]. IHSR blocking probability is more or less 10% lower than the MH one.

The proposed routing algorithm reduces the congestion over the IHLs managing a greater number of active connections; thus, a greater part of the satellite resources over the return link can be saved and used for other kind of applications; moreover, if the percentage of active

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outer connections is lower than 70%, all the connections can be managed through the IHLs without using the satellite return link using the proposed algorithm.

This is a great result because it is known that the satellite return link is a very expensive resource; moreover, the high propagation delay over the GEO satellite link is a hot issue for real-time application.

The PLR index over the satellite return link agrees with the previous considerations. As shown in Figure 9, when the satellite link throughput is close to 90%, the MH approach does not guarantee a good QoS to the multimedia connections; in contrast, using the IHSR algorithm, the packet loss value over the satellite link is always under the threshold of $10^{-2}$ because a greater number of connections is managed over the IHLs unloading the satellite link.

Figure 10 shows the maximum percentage of traffic connection that is possible to route out of the HAP coverage area in all simulated scenarios without exceeding the 1% PLR threshold. The better usage of IHL resource allows IHSR algorithm to better perform compared to MH.

In conclusion, the IHSR algorithm presents a lower block probability and packet loss compared to the MH one; moreover using the new approach, the throughput is higher on the IHLs and lower on the satellite return link. In this way it is possible to efficiently manage resource requests allowing an elevated multiplexing of multimedia traffic and guaranteeing the agreed QoS.

### 6.3 Varying the Network Dimension

The second simulation campaign has been conducted with the aim of highlighting in which way some system parameters as utilization and PLR over the IHLs are strictly related to the network dimension. In particular, we are interested in evaluating the system behavior when the number of platforms in the HAP’s layer increases.

In this campaign, only the multimedia traffic source with a mean data rate equal to 1000 kB/s has been used in order to reduce the simulation time that remarkably increases with the network dimension.

It would be necessary to use a parallel distributed computing architecture for simulating the data transmission through the aerial platforms because this problem is a well-known distributed problem but we realized software based on an “actor model scheduler” that is mostly suitable for our single processor computer architectures; in summary, we can think of an actor as a finite-state machine that evolves through a life cycle that is a succession of states of behaviors. An actor is a reactive object, responding to incoming messages on the basis of its current state and message content. Message reception is implicit, and there is no receive primitive. An actor is...

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**Figure 8:** Satellite return channel throughput: scenarios A, B, and C.

**Figure 9:** Satellite return channel PLR: Scenarios A, B, and C.

**Figure 10:** Maximum percentage of supported outer connections.
at rest until a message arrives. The message processing triggers a state transition and the consequent execution of an action. Because action execution is atomic, it cannot be preempted or suspended. At the action termination the actor is ready to process a next message and so forth. Actors do not have internal threads for message processing. At most one action can be in progress in an actor at a given time. More details about the “actor model” can be found in [29-31].

Figure 11 shows the HAP’s constellation dimensions analyzed in this simulation campaign.

In Figure 12, the utilization over the IHLs increases from 60%, for the 2×2 dimension, and to 92%, for the 6×6 dimension in which the set of paths between two different coverage areas is big enough to satisfy the transmission requests. The utilization of the IHLs is strictly related to the amount of aerial platforms belonging to the HAP’s layer, even if, the offered load in terms of connections asking for services in each coverage area is a fixed value. This system behavior is due to the specific network dimension because each platform can send its own data using its own IHLs but it can also receive data from its neighbors over the same IHLs. Using a small dimension for the HAP layer, IHLs work in an underutilization condition because the HAP’s return links have a bandwidth capacity of 34.8 Mb/s whilst the IHLs can manage a bandwidth of 96 Mb/s that cannot be filled using traffic load coming only from few platforms.

Obviously augmenting the number of platforms also increases the number of links in the networks and the length of the transmission paths between a source and a destination; for this reason the average utilization over the IHLs increases also causing more packet loss as shown in Figure 13. This analysis provides a way for dimensioning the HAP layer in terms of number of platforms to maximize the overall throughput; as we can see, according to the bandwidth capacity values for both the HAP return link and IHLs, it is useless to design an HAP layer hosting more than 25 platforms because beyond this dimension, the average IHL utilization saturates around 90% but the packet loss becomes a big issue.

The very high utilization value of the 6×6 constellation causes a high packet loss on the IHLs equal to 4.5% that is over the admission QoS threshold of 1%; thus on increasing the number of platforms belonging to the constellation, the packet loss value also increases and sometimes the agreed QoS cannot be guaranteed.

According to the obtained results, only the 2×2 and 3×2 dimensions can satisfy the QoS constraints under all simulation conditions, also varying the percentage of outer connections.

When the number of platforms belonging to the HAP layer increases, it is necessary to reduce the number of connections managed through the IHLs in order to have a packet loss value in agreement with the multimedia traffic source requirements in terms of QoS.

Figure 14 shows maximum utilization values that are reached on the IHLs respecting the QoS parameters and varying the HAP layer dimension; this value decreases when the layer’s dimension increases. Anyway, it is possible to note that the throughput value is not too bad because it is always between 70% and 76%.

The same system behavior is shown in Figure 15 concerning the connection block probability on the IHLs. A good value of this index (i.e., 4–5%) can be reached only when the percentage of outer connections is in agreement with the values pointed out in the
Taking into account all the previous considerations, it is feasible to choose the right dimension respecting the QoS required by end users and trying to avoid the congestion of IHLs that are the real bottleneck of this system architecture.

In conclusion, this second simulation campaign has demonstrated that many system parameters are strictly related to the network dimension of the HAP layer; particularly the PLR and the throughput over the IHLs increase when the number of aerial platforms belonging to the HAP layer increases.

Anyway, it has been possible to highlight few system load thresholds under which a good overall system behavior, in terms of QoS offered to the traffic connections, is always guaranteed. These system load thresholds depend on the number of aerial platforms belonging to the HAP layer and the percentage of outer connections.

7. CONCLUSIONS

This paper makes clear how the integration of different layered networks is becoming one of the most important features in the future telecommunication systems explaining the potential role of an integrated satellite-HAP-terrestrial system and proposing a new multilayered inter-HAP-satellite routing algorithm. The conducted simulation analysis has verified the goodness of the proposed routing strategy joined to a well-suited connection admission control scheme for the whole multilayered communication architecture. The proposed routing algorithm reduces the congestion over the IHLs managing a greater number of active connections; thus, a greater part of the satellite resources over the return link can be saved and used for other kinds of applications. Finally, the analysis conducted varying the HAP layer dimension has pointed out the connections between quality indexes (i.e., throughput, packet loss) and the aerial platforms numerosness, providing a way for an effective network deployment.

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