Network Layer Integration of Terrestrial and Satellite IP Networks over BGP-S

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Abstract- **To accomplish network layer integration of terrestrial and satellite IP networks, special exterior gateway protocols are needed. In this work, a new exterior gateway protocol called** *Border Gateway Protocol - Satellite version* **(BGP-S) is introduced that enables automated discovery of paths that go through the satellite network. This protocol is designed to work in only one terrestrial gateway in every Autonomous System and enables the forwarding of discovered paths in the Internet using the BGP-4 protocol.**

Keywords: **IP-Based Routing, Satellite Networks, BGP-4, Exterior Gateway Protocol.**

I. Introduction

Satellite networks are becoming increasingly important for global communications. With the explosive growth of the Internet, the IP technology is being pushed to the satellite networks. To realize this, satellites carry IP-switches that forward packets independently. These IP-switches are connected to each other as well as to ground stations. Several issues related to IP-based satellite networks have been reviewed in [1]. Routing in the LEO satellite environment is a challenging problem because of the dynamic nature of the satellite networks. In recent years, several routing algorithms and protocols have been proposed for IP-based LEO satellite networks [2], [3], [4].

However, the use of the IP-based satellite networks as a part of the Internet cannot be accomplished only by solving the routing problem. The integration of the IP-based satellite networks must assure their interoperability with the terrestrial IP networks. Previously, satellite network integration issues have been pointed out in [5], [6], [1]. As suggested in these papers, the satellite network can be viewed as a separate Autonomous System (AS) with a different addressing scheme. Terrestrial gateways act as border gateways on behalf of the satellite network and perform the address translations. Then, paths over both networks can be discovered using an Exterior Gateway Protocol such as BGP [7]. However, since the internal and external metrics for terrestrial ASs and the satellite network are different, special care must be taken. None of the studies mentioned above provides a detailed solution as how this network level integration can be accomplished.

In this work, we propose the *Border Gateway Protocol - Satellite version* (BGP-S). The satellite network is considered as an AS with special properties. BGP-S is designed to coexist with the BGP-4 [7] and support automated discovery of paths that include the satellite hops. It is designed to be implemented in only one terrestrial gateway in every AS that is connected to

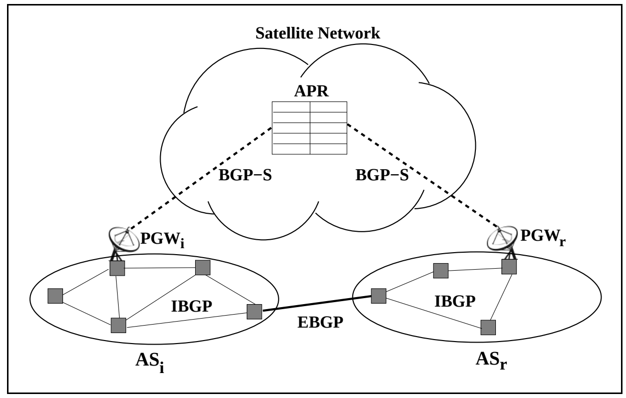

Fig. 1. The Hybrid Terrestrial/Satellite Network Architecture

the satellite network. Since the delay in the satellite network can be much longer than in a terrestrial AS, the acceptance of paths involving satellite hops is accomplished through active delay measurements. The general hybrid network architecture is introduced in Section II. In Section III, details of packet forwarding scheme is explained. The BGP-S protocol is described in detail in Section IV. Finally, Section V concludes this paper.

II. The Hybrid Terrestrial/Satellite Network Architecture

The general hybrid network consists of the terrestrial Internet and an IP-based satellite network. The terrestrial Internet is organized into Autonomous Systems (ASs). Inside every AS, the routing is accomplished through *Interior Gateway Protocols* (IGPs). The inter-AS routing is based on an *Exterior Gateway Protocol* (EGP), specifically, *Border Gateway Protocol version 4* (BGP-4) [7]. The satellite network should carry the following properties:

- The satellite network should be able to forward individual data packets between two gateways on the Earth with its own addressing scheme.
- There is no constraint on the satellite topology as long as any two terrestrial gateways can be connected over the satellite network.
- There is no constraint on the routing protocol used in the satellite network.

The following is a list of notations used in this work:

- **Autonomous System:** The collection of routers under the same technical and administrative control is referred to as an

Autonomous System. We denote the autonomous systems by AS_i as shown in Figure 1.

• **Routers and BGP Speakers:** The routers in every autonomous system AS_i are denoted by $R_{i,j}$, for $j = 0, \cdots, \mathbf{N}_i^R - 1$, where $\mathbf{N}_i^R$ is the number of routers in AS_i. The BGP speakers are the routers that implement BGP and they are denoted by $BS_{i,j}$, for $j = 0, \cdots, \mathbf{N}_i^{BS} - 1$, where $\mathbf{N}_i^{BS}$ is the number of BGP speakers in AS_i. Note that $\mathbf{N}_i^{BS} \leq \mathbf{N}_i^R$ and $\{BS_{i,j}\} \subseteq \{R_{i,j}\}$.

• **Network Address:** A network address NA_i is the longest common IP prefix shared by the network elements in that subnetwork. An example network address is `193.140.196.0/24`.

• **AS Path:** An AS path $\mathbf{P}^j_{AS_i}(NA_k)$ is an ordered list of autonomous systems $(AS_i, \cdots, AS_x)$, which is the j^{th} alternative path for AS_i to reach the network address NA_k, where NA_k resides in AS_x.

• **Gateways and Peer Gateways:** The gateways are the terrestrial stations that enable the communication between the autonomous systems and the satellite network. In an autonomous system AS_i, the number of gateways is $\mathbf{N}_i^{GW}$, and the gateways are denoted by $GW_{i,j}$, for $j = 0, \cdots, \mathbf{N}_i^{GW} - 1$. One of the gateways is designated as the peer gateway and implements the BGP-S protocol used for path discovery over the satellite network. The peer gateway in an autonomous system AS_i is denoted by PGW_i as shown in Figure 1. A peer gateway is a gateway, a router, and a BGP speaker at the same time.

• **Active Peer Register:** The active peer register (APR) is the list of active peer gateways connected to the satellite network. APR can be maintained on the Earth as well as in the satellite network, where it can be reached by peer gateways over preconfigured paths. APR can also be duplicated as long as all copies are updated in real-time.

Additionally, the terrestrial network contains routers and hosts, and there are satellites with on-board routers. The satellites are denoted by S_i, for $i = 0, \cdots, \mathbf{N}^S - 1$, where $\mathbf{N}^S$ is the number of satellites. Note that we do not assume any satellite constellation or organization of the satellites. Thus, we only use the index i in S_i to refer to the satellites.

III. Packet Forwarding

The packet forwarding from one terrestrial gateway to the next occurs with “IP over IP” tunneling in the satellite network. Under this scheme, the packets are encapsulated individually into native satellite packets before they are sent to the satellite network by the terrestrial gateway. The native satellite packets carry the address of the next terrestrial gateway which can be interpreted by all satellites in the network. Hence, the satellites do not need to keep track of all IP addresses. It is assumed that the addressing scheme used by the satellite network and the mappings of these addresses to IP-addresses are available in the terrestrial gateways. While the routers in the terrestrial network continue using the standard packet forwarding procedures, the terrestrial gateways must translate the IP addresses and encapsulate the IP packets into native satellite packets.

Definition 1. (Next Hop Function *NH*). Let P denote a packet received by a terrestrial gateway. The function $NH(P)$ returns the next hop on the path of the packet P towards its destination.

Definition 2. (Satellite Next Hop Function *SNH*). Let P denote a packet received by a terrestrial gateway $GW_{i,j}$, and the next hop for packet P be a terrestrial gateway $GW_{r,s}$, i.e., $NH(P) = GW_{r,s}$, where $(r,s) \neq (i,j)$, which is reachable through satellite network. The function $SNH(GW_{r,s})$ returns the satellite S_t, where $GW_{i,j}$ should first send the packet P to such that P reaches $GW_{r,s}$.

Upon receiving a packet P, a terrestrial gateway $GW_{i,j}$ processes the packet as follows:

1. The gateway determines the next hop $NH(P)$ for the received packet P.
2. If the packet's next hop is not a terrestrial gateway, i.e., $NH(P) \notin \{GW_{r,s} \mid (r,s) \neq (i,j)\}$, it forwards the packet to the next hop without any modifications.
3. If the next hop of the packet P is a terrestrial gateway, i.e., $NH(P) = GW_{r,s}, (r,s) \neq (i,j)$, then P is encapsulated into a native satellite packet with $GW_{r,s}$ as the destination and sent to its next hop S_t in the satellite network, where $S_t = SNH(GW_{r,s})$.

Note that it is assumed that no two terrestrial gateways are connected to each other with terrestrial links. If it is the case, then the function *NH* should be modified such that it also indicates if the next hop should be reached through the satellite network or over a direct terrestrial link. When a terrestrial gateway receives a native satellite packet from a satellite, it simply extracts the payload from the satellite packet and processes it as a regular IP packet.

IV. The BGP-S Protocol

To allow the automated discovery of paths that pass through the satellite network, we introduce a new protocol called the *Border Gateway Protocol - Satellite version* (BGP-S). BGP-S has the same basic functionality as the BGP-4 [7]. However, using the BGP-S together with BGP-4 [7] has two main advantages. First of all, the satellite network does not directly participate in the path calculations. Instead, it is only responsible for carrying data packets and (possibly) keeping track of the active peer gateways. Secondly, if the satellite network is regarded as a regular autonomous system, there would not be any difference between a terrestrial AS and the satellite network. This may be misleading in many cases since the delays in the satellite network are much larger than in a terrestrial AS. Therefore, under BGP-4 [7], it is necessary to manually configure the routing strategies according to the location of the

ASs and delay estimations. The BGP-S eliminates the need for manual configuration and enables automatic adaptation based on the delays in the satellite and terrestrial networks.

In the hybrid network model, BGP-4 and BGP-S are used together as shown in Figure 1, where APR is located in the satellite network. Between the terrestrial BGP speakers, the BGP-4 protocol is used. More specifically, the Interior-BGP (IBGP) is used among the BGP speakers in the same AS. The BGP speakers that belong to different ASs use Exterior-BGP (EBGP). Although the message formats are the same both for IBGP and EBGP, there are differences in message processing. The peer gateways communicate over the satellite network using the BGP-S protocol. The peer gateways must implement both BGP-4 and BGP-S.

There are two important rules in a system implementing the BGP-S:

Rule 1. There is only one peer gateway in an AS.

Rule 2. The routing policies that are configured for the BGP-4 are automatically adopted by BGP-S.

The first rule aims to limit the number of peer gateways to the number of ASs directly connected to the satellite network. Furthermore, it eliminates duplication of information received in an AS. The second rule ensures that BGP-S is fully compatible with the BGP-4 protocol, hence with the existing Internet infrastructure. These rules may include elimination of paths that contain certain ASs, ensuring that transit traffic is not carried, etc. Detail description of BGP-4 can be found in [7].The details of the BGP-S protocol are provided in the following sections.

A. BGP-S Connection Setup

The BGP-S protocol uses TCP connections between two peer gateways for communication. A BGP-S connection is closed either by an explicit *NOTIFICATION* message or when no messages are received from the other party within a predetermined time-out period. Considering the number of active peer gateways, the time-out period is suggested to be longer than in BGP-4, approximately 10 seconds. The connection setup is accomplished through the following steps, as also shown in Figure 2:

1. When a peer gateway PGW_i becomes active and wants to connect to other peer gateways, it sends an *Alive(PGW_i)* message to the Active Peer Register (APR).
2. The APR sends a list of already active peer gateways to PGW_i.
3. PGW_i acknowledges the reception of the active peer gateway list to the APR.
4. The APR sends to all other active peer gateways the *Alive_Fwd(PGW_i)* to notify them about the availability of the peer gateway PGW_i.

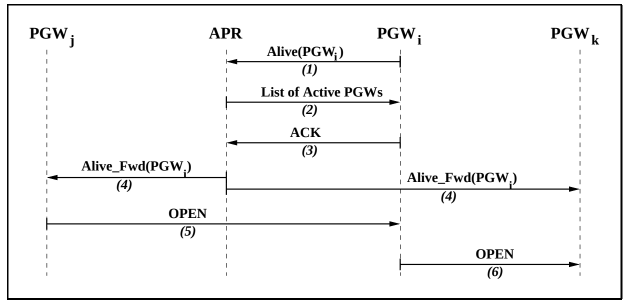

Fig. 2. The Activation of Peer Gateways and Connection Setup

5. If an already active peer gateway PGW_j wants to establish a BGP-S connection, then it sends an *OPEN* message to PGW_i.
6. PGW_i can establish a BGP-S connection to any other peer gateway PGW_k in the active peer register by sending an *OPEN* message.

The *Alive(PGW_i)* message contains the IP and satellite network addresses of the peer gateway PGW_i as well as the AS number where PGW_i resides. The *Alive_Fwd(PGW_i)* message contains the same information as the *Alive(PGW_i)* message. The difference is that *Alive()* messages are created by the peer gateways that become active, and *Alive_Fwd()* messages are created by the APR to notify other peer gateways of the availability of a new peer gateway. The *OPEN* message has the same format as in the BGP-4 protocol.

B. Path Discovery and Prioritization

A peer gateway learns paths both via BGP-S and BGP-4. If it decides to advertise the paths to other peer gateways over BGP-S, then it uses *UPDATE* messages which have the same format as in BGP-4. It is important to note that the paths learned via BGP-S cannot be processed like the paths learned through BGP-4. While processing these paths, it is important to be consistent with policies configured with the BGP-4 protocol. Then, the paths are compared based on the delay to the target network. Note that the delay comparison is just an approximation of the real-time delay. The delay changes continuously due to fluctuations in the traffic load and it is not feasible to check the delay to all possible network addresses periodically. In order to discover the delay to a given network, the following new messages are used:

***POLL()* Message:** The *POLL* message is used to request a delay measurement to a specified network or network element. The *POLL(PGW_i, PGW_j, A)* is a message sent by the peer gateway PGW_i to PGW_j to learn about the delay between PGW_j and A, where A can be a network or a network element. Every *POLL* message contains the message creation timestamp.

***DELAY()* Message:** The *DELAY()* message is a reply to a

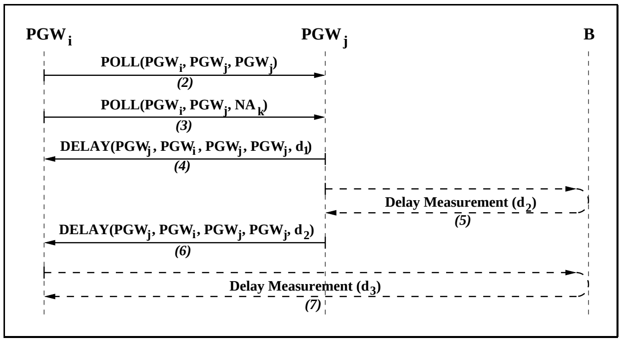

Fig. 3. The Processing of AS Paths Learned via BGP-S

POLL() message. The *DELAY*(PGW_j, PGW_i, A, B, d) is a message sent by the peer gateway PGW_j to PGW_i telling that the delay between itself and an network element B in the network A is d. If A is a network element, then $A = B$.

If $A = PGW_j$, then *DELAY()* is like a ping response; the receiving peer gateway PGW_j replies immediately with a delay equal to the timestamp in the *POLL()* message. Then, the peer gateway PGW_i calculates the round trip delay to PGW_j. If A is a network address, then PGW_j measures the delay to the network element B in the network A. Then the *DELAY()* message contains this measured delay as d. When the delay to a network A is needed, PGW_j selects a network element B in the network A and measures the delay from itself to B. The delay can be measured using the ping utility. However, any other method can be used for delay measurement, as well.

B.1 New Path Discovery via BGP-S

Assume a peer gateway PGW_i learns from PGW_j via BGP-S the AS path $\mathbf{P}_{AS_j}(NA_k)$ to reach the network NA_k. The new AS path $\mathbf{P}_{AS_j}(NA_k)$ is processed following the steps below, which are also shown in Figure 3.

1. PGW_i checks $\mathbf{P}_{AS_j}(NA_k)$ with the policies setup for BGP-4 protocol. If there is a conflict, then $\mathbf{P}_{AS_j}(NA_k)$ is discarded.
2. If $\mathbf{P}_{AS_j}(NA_k)$ conforms with the BGP-4 policies and the delay from PGW_i to PGW_j is not available to PGW_i, then PGW_i sends a *POLL*(PGW_i, PGW_j, PGW_j) message to PGW_j.
3. PGW_i also sends a *POLL*(PGW_i, PGW_j, NA_k) message to PGW_j to learn the delay between PGW_j and the network NA_k.
4. PGW_i receives the *DELAY*(PGW_j, PGW_i, PGW_j, PGW_j, d_1) message from PGW_j. The delay d_1 to PGW_j, is estimated as the half of the difference of the current time T_{cur} and the timestamp d, i.e., $d_1 = \frac{T_{cur}-d}{2}$.
5. PGW_j measures the delay d_2 to the network element B in network NA_k.
6. PGW_i receives the *DELAY*(PGW_j, PGW_i, NA_k, B, d_2) message from PGW_j.
7. PGW_i measures the delay d_3 to B if there exists an AS path $\mathbf{P}_{AS_i}(NA_k)$ to reach the network NA_k in the Routing Information Base (RIB) of BGP-4. If there is no such entry in the BGP-4 RIB, then the delay to B is assigned infinity, i.e., $d_3 = \infty$.
8. If d_3 is infinity, then $\mathbf{P}^1_{AS_i}(NA_k)$ is created by appending AS_i to $\mathbf{P}_{AS_j}(NA_k)$ and inserted to BGP-4 RIB with a default local preference value.
9. Assume that there is already an AS path $\mathbf{P}^*_{AS_i}(NA_k)$ used in AS_i to reach the network NA_k such that $\mathbf{P}^*_{AS_i}(NA_k) = \arg\max_{X \in \{\mathbf{P}_{AS_i}(NA_k)\}} LocalPref(X)$, where the function $LocalPref(X)$ gives the local preference value of the AS path X. If $d_1 + d_2 \geq d_3$, i.e., the new path over the satellite network is longer than the already available AS path, then the new AS path $\mathbf{P}^{p+1}_{AS_i}(NA_k)$ is inserted into BGP-4 RIB with a local preference value of $LocalPref(\mathbf{P}^*_{AS_i}(NA_k)) - 1$, where p is the number of AS paths to NA_k already in the RIB.
10. Under the same conditions as in the previous step, if $d_1 + d_2 < d_3$, i.e., the new path over the satellite network is shorter, then the new AS path $\mathbf{P}^{p+1}_{AS_i}(NA_k)$ is inserted into BGP-4 RIB with the local preference value of $LocalPref(\mathbf{P}^*_{AS_i}(NA_k)) + 1$, where p is the number of AS paths to NA_k already in the RIB.

When an AS path is inserted into the BGP-4 RIB by a peer gateway, the delay information remains local to the BGP-S protocol. The delay comparison is advertised to the BGP speakers in the same network implicitly with the local preference value. Although a relative local preference assignment is not allowed under BGP-4, BGP-S assigning relative local preference values does not affect the integrity of the BGP-4 because there is only one network entity per AS that is allowed to perform this operation.

B.2 New Path Discovery via BGP-4

Assume that a new AS path $\mathbf{P}^{p+2}_{AS_i}(NA_k)$ is advertised via BGP-4, which has a higher local preference value than the currently used, i.e., $LocalPref(\mathbf{P}^{p+2}_{AS_i}(NA_k)) > LocalPref(\mathbf{P}^*_{AS_i}(NA_k))$. Also let $\mathbf{P}^q_{AS_i}(NA_k)$ be the AS path with the best delay performance to the network NA_k among the AS paths learned via BGP-S. The peer gateway PGW_i performs the following steps to process the new AS path:

1. If the BGP-4 RIB does not contain any path to NA_k that was learned via BGP-S, then no action is taken.
2. Otherwise, the delay to the network element B in NA_k is measured for $\mathbf{P}^{p+2}_{AS_i}(NA_k)$ and $\mathbf{P}^q_{AS_i}(NA_k)$. The measurements are taken following the Steps 2-7 in Section IV-B.1, obtaining the delays d_1,d_2, and d_3.
3. If $d_1 + d_2 \geq d_3$, i.e., the AS path over the satellite network $\mathbf{P}^q_{AS_i}(NA_k)$ is longer than the new AS path $\mathbf{P}^{p+2}_{AS_i}(NA_k)$, then no action is taken.
4. If $d_1 + d_2 < d_3$, i.e., the AS path over the satellite network $\mathbf{P}^q_{AS_i}(NA_k)$ is shorter than the new AS path $\mathbf{P}^{p+2}_{AS_i}(NA_k)$,

then PGW_i updates the local preference of $\mathbf{P}^q_{AS_i}(NA_k)$ as *LocalPref*$(\mathbf{P}^{p+2}_{AS_i}(NA_k)) + 1$. Then, PGW_i advertises the path $\mathbf{P}^q_{AS_i}(NA_k)$ with the updated local preference value.

B.3 Path Withdrawal

When a path is withdrawn either via BGP-4 or BGP-S, the peer gateway PGW_i in AS_i must check the RIB and possibly modify the local preference value of the shortest AS path that goes over the satellite network. Assume that there are p paths in the BGP RIB to reach the network NA_k. Upon receiving an *UPDATE* message that contains the withdrawal of an AS path that leads to NA_k, the peer gateway PGW_i performs the following operations:

1. If the withdrawn AS path is not the one that is currently used, no action is taken.
2. If the currently used path is withdrawn and the AS path with the next highest local preference value is learned via BGP-4, then no action is taken.
3. If the AS path with the next highest local preference value is learned over BGP-S, then the AS path that is learned via BGP-4 and has the largest local preference value is found, which we call $\mathbf{P}^t_{AS_i}(NA_k)$.
4. All AS paths with larger local preference values than $\mathbf{P}^t_{AS_i}(NA_k)$ are collected in the set $\mathbf{P}^{Sat}_{AS_i}(NA_k)$.
5. The delays of all AS paths in $\mathbf{P}^{Sat}_{AS_i}(NA_k)$ are measured as described in Section IV-B.1, Steps 2-7. The delay of $\mathbf{P}^t_{AS_i}(NA_k)$ is also measured as described in these steps.
6. Let us assume that the AS path $\mathbf{P}^s_{AS_i}(NA_k)$ has the lowest delay d_s among all paths in $\mathbf{P}^{Sat}_{AS_i}(NA_k)$. Also assume that the delay of $\mathbf{P}^t_{AS_i}(NA_k)$ is d_t. If $d_t < d_s$, i.e., all AS paths over the satellite network are longer, then the local preference values of all AS paths in $\mathbf{P}^{Sat}_{AS_i}(NA_k)$ are set to *LocalPref*$(\mathbf{P}^t_{AS_i}(NA_k)) - 1$, i.e., *LocalPref*$(\mathbf{P}) =$ *LocalPref*$(\mathbf{P}^t_{AS_i}(NA_k)) - 1$, $\forall \mathbf{P} \in \mathbf{P}^{Sat}_{AS_i}(NA_k)$.
7. If $d_t > d_s$, one of the AS paths over the satellite network is shorter, then the local preference values of all AS paths in $\mathbf{P}^{Sat}_{AS_i}(NA_k)$ except for $\mathbf{P}^s_{AS_i}(NA_k)$ are set to *LocalPref*$(\mathbf{P}^t_{AS_i}(NA_k)) - 1$, i.e., *LocalPref*$(\mathbf{P}) =$ *LocalPref*$(\mathbf{P}^t_{AS_i}(NA_k)) - 1$, $\forall \mathbf{P} \in \mathbf{P}^{Sat}_{AS_i}(NA_k)$ and $\mathbf{P} \neq \mathbf{P}^s_{AS_i}(NA_k)$. The local preference value of $\mathbf{P}^s_{AS_i}(NA_k)$ is set to *LocalPref*$(\mathbf{P}^t_{AS_i}(NA_k)) + 1$.
8. The updated local preference values are advertised in the autonomous system AS_i.

C. BGP-S Connection Termination

Assume that a BGP-S connection between two peer gateways PGW_i and PGW_j is terminated because PGW_j does not receive any message from PGW_i within a time-out period. If the connection terminates due to time-out, PGW_j notifies the APR about the termination. APR checks if PGW_i alive. If PGW_i is alive, no action is taken. If PGW_i does not respond, then APR records this in its database and informs all active peer gateways about this. Any existing connections to PGW_i is terminated and all RIB entries that use AS_i are withdrawn by active peer gateways within their ASs.

On the other hand, if a peer gateway PGW_i will be turned off or if AS_i does not want to receive any traffic from the satellite network, then PGW_i terminates all active connections with *NOTIFICATION* messages. The peer gateways that receive *NOTIFICATION* messages do not contact APR. Then PGW_i sends a message to APR indicating that it is no longer active. APR records this in its database and forwards this message to all active peer gateways. All RIB entries that use AS_i are withdrawn by active peer gateways.

V. Conclusion

In this work, we introduced the BGP-S protocol for integration of the IP-based satellite networks with the Internet. The BGP-S protocol does not require a special satellite network architecture and works independent of the internal routing of the satellite network. BGP-S is fully compatible with the BGP-4 protocol. It uses BGP-4's *LocalPref* value to propagate the paths it learns through the satellite network. To accept or reject the paths learned through the satellite network, the policies manually configured in the routers are given priority. If alternative paths are available, the choice is based on measuring the delays on the existing paths. BGP-S is implemented only in one terrestrial gateway in every terrestrial AS to reduce the complexity.

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