Proof of concept of AITRON applied to LEO satellite systems

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***Abstract*— In a context characterized by the availability of multiple networks and communication systems, a key goal is that applications are able to get the most of the underlying networks, meeting their requirements and constraints while still co-existing in a controlled way with other applications and users. In this context, our aim is to develop a communications manager (named AITRON) that facilitates robust and highly flexible connectivity for all types of applications, particularly those requiring real-time operations and supporting highly critical services. As part of this broader objective, this paper examines how this concept can be applied to a communication network based on a Low Earth Orbit (LEO) satellite constellation using inter-satellite links. This paper presents the various architectural elements of a reference LEO routing solution and its general operational principles, which are based on Software Defined Networking concepts. Then it discusses how such a solution could be integrated with an AITRON-type orchestrator. Finally, it presents the validation environment to be used and the AITRON roadmap.**

Keywords*— *LEO, routing, software defined networking, network orchestrator, network architecture

I. Introduction

In a context characterized by the availability of multiple networks and communication systems, a key goal is that applications are able to get the most from the underlying networks, meeting their requirements and constraints while still co-existing in a controlled way with other applications and users. This objective entails the development of specific communication management solutions, which can operate over multiple planes (data, control, and management) and which can intelligently orchestrate user traffic by integrating highly heterogeneous networks.

II. The AITRON Communication manager

A. Concept and objectives

The exchange of information between two endpoints in an IP packet network implies the provision of two principal services. Firstly, there is the connectivity between these endpoints (that is, that any packet sent by one endpoint reaches the destination) and secondly the guarantee of the QoS (Quality of Services) throughout the path, which implies the enforcement of per-hop packet processing mechanisms as well as QoS-based routing policies.

To provide these services, we can find many standardized solutions available nowadays such as the combination of QoS policies by using scheduling and queueing mechanisms and dynamic routing protocols with Traffic Engineering capabilities.

When a node makes routing decisions the knowledge of the status of the whole network (that is, not only its immediate neighbours but also beyond them covering the whole topology as well as the status of the links) is very important to optimize the usage of network resources. It may be necessary to rely on protocols that discover network topology so that routes can be calculated and applied on the user plane traffic.

However, there exist important challenges when these services must be provided under scenarios with many nodes, highly frequent changing topology or the links between nodes are very unstable (for example, when nodes are on moving assets with a wireless link). Despite the fact there exist routing technologies for MANET [1] that were thought to cope with these cases, they still have limitations in network convergence and may temporarily provoke conflicts in such routing decisions.

Furthermore, we must face the QoS guarantee of very heterogeneous IP traffic using the same network resources, especially critical traffic with very high requirements regarding low latency.

So, a correct orchestration and an efficient usage of the network resources under very unstable topology is the key for providing good communications services to the endpoints and AITRON is aiming this objective.

B. General architecture

AITRON will play the role of a smart router (layer 3) making all the end-to-end routing decisions. In Fig. 1 we can see the AITRON's architecture.

It will offer an abstraction layer hiding the complexity of the underneath topology to the user endpoint, which would see AITRON as a forwarder of the user plane traffic to the destination and as an enforcer of the QoS policies needed for each type of IP traffic (administrated by the Network Resources Manager).

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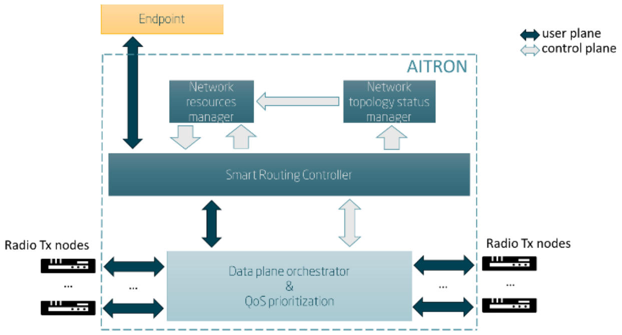

Fig. 1. AITRON architecture

Whenever AITRON must enforce a routing policy (decided by the Smart Routing Controller) that implies the transmission of IP traffic towards a next hop, it uses the packet forwarding services offered by the underlying radio networks.

These may range from civil 5G / 6G networks to satellite networks and even military ad-hoc networks, each of them with very different radio technology and system architectures and allowing different levels of integration.

Depending on the waveform and forwarding techniques implementation these networks may implement different topologies by themselves like for example point-to-point, mesh and/or star networks. They may also implement data reliability services and in some cases even QoS prioritization.

AITRON will use all these forwarding services to apply and enforce its routing decisions and to assure end-to-end QoS.

In the figure Fig. 1 we can see the radio network transmission nodes becoming the gate to send and receive IP packets with a neighbour node. The technology used to implement each underlying radio network represents an additional challenge. AITRON will accommodate the forwarding and QoS assurance capabilities of each of them to enforce QoS policies hop by hop.

In the control plane AITRON exchanges data with neighbour nodes to share and report its own radio links status as well as its knowledge about the status of the rest of the network, which is gathered by the Network Topology Status Manager.

C. *Traffic orchestration approach*

The orchestration of the whole IP traffic exchanged in a network with frequently changes in its topology implies making precise routing decisions to guarantee QoS end-to-end. Furthermore, these routing decisions must be enforced for each QoS class traffic throughout the whole path and corrected whenever a topology change happens to minimize any transitory packet loss.

These QoS based routing decisions may be taken completely distributed in each node assuming a shared common knowledge of the topology and status of network. However, a point will be reached where the routing decisions made by several nodes may collide and provoke inefficient usage of the network resources.

As an alternative approach the orchestration may be centralized allowing a node to have a holistic view of the whole network status. This central node would make better decisions on behalf of all the nodes.

An enabler technology that may implement this approach is Software Defined Network (SDN), where a node plays the role of the controller of the whole network and the rest are just forwarders of the user plane applying the decisions made by the controller. Furthermore, this technology opens the door to introduce network virtualization applications that help the QoS assurance, such as network slicing.

However, this approach does not exempt from important challenges that must be addressed, such as the limitations of the topology discovery and the single point of failure.

D. *The importance of predictive communications*

Regardless of how good the orchestration approach is (either distributed or centralized), there will always be potential packet losses in the interval of topology change discovery and the routing decisions enforcement. This is because it is a reactive approach and, until an event is not detected, the routing policies modifications cannot be calculated and applied.

So here is when the Artificial Intelligence (AI) technology can play an important role to minimize these packet losses and make possible that services with very high criticality may be used even in the worst instability scenarios. If the topology as well as link status changes could be predicted with enough anticipation routing decisions could be made and applied in advance accordingly.

With well-trained algorithms any topology alteration would be predicted with a very high probability and then the services whose traffic has the highest QoS demands in terms of latency and packet loss could be used.

III. APPLICATION TO A LEO SATELLITE CONSTELLATION

A. *LEO satellite use case*

As a possible use case for AITRON, we may consider two remote nodes communicating with a satellite which is part of a Low Earth Orbit (LEO) satellite constellation. Traffic has to traverse several other communication networks before reaching the LEO satellite system, each of them with different levels of integration with AITRON. Due to security related issues, we can assume that the traffic of one destination may not traverse a specific country, while for the other destination latency is a critical factor.

The AITRON would orchestrate traffic by interfacing or integrating with the routing solution of this LEO satellite constellation.

B. *Description of the Startical LEO Constellation*

We take as reference the routing solution developed in-house for the forthcoming STARTICAL system [2], which has as target to provide safety critical real-time communication for air traffic control services in oceanic and remote areas, using a nearly polar LEO constellation composed of around 300 small satellites and multiple ground stations. STARTICAL will be the first satellite platform for air navigation that includes, alongside aircraft position surveillance services (ADS-B), a VHF radio communication system between the controller and the pilot compliant with aeronautical standards. These new services will enhance safety, capacity, efficiency, and punctuality of flights, providing clear benefits for both airlines and passengers.

To support these communication services, it is expected that the satellites will be interconnected with other satellites in the same planes and satellites in other planes using optical inter-satellite links (ISL), based on low size and low weight laser products targeted for the CubeSat market. Additionally, satellites will be able to connect using conventional links to ground stations (GS) located in key locations according to the communication service's needs.

C. Routing solution objectives

LEO satellite constellations can be described as highly dynamic environments, where satellite movements cause frequent, although generally predictable changes in the network topology. These networks are characterized by a discontinuous operation of ISLs, especially of cross-plane ISLs in polar areas, and by short contact times between satellites and ground stations (in the order of a few minutes). To support safety-critical ATM services using the STARTICAL LEO constellation, it is necessary that the routing elements on-board and on-ground can also cope with other predictable and unpredictable topology changes resulting from node failures or degraded channel conditions.

The routing solution is thus a control plane software that interfaces the IP packet forwarding mechanisms of the LEO constellation satellite and ground nodes and that provides robust, low latency and low loss connectivity among all nodes despite frequent changes in topology and potential link or node failures.

D. General concept and architectural elements

The routing solution design for our reference system is based on a centralized routing approach, following a Software Defined Networking approach, and is thus fully aligned with the AITRON architectural principles.

Routing configuration is generated regularly by a central element on ground - the Routing Controller – which - based on the predicted behaviour of the topology and considering specific routing criteria - provides configuration information covering an extended time period.

In order to be robust in front of unexpected failure events, this scheme also includes failure recovery mechanism that are pre-configured and initially activated automatically for ultra-fast recovery and then adjusted with the support of the Ground Nodes for routing optimization. Recovery mechanisms have been defined in such a way that the Routing Solution is robust in front of inter-satellite and feeder link failures and in front of satellite and ground node failures, including multiple failure scenarios. The design includes also a set of protection mechanisms to ensure connectivity even in rare, non-nominal conditions.

The Routing Solution architecture has three components, described in more detail below.

- *Routing Controller.* Based on inputs regarding the predicted topology and link / node status of the system obtained from the constellation system management entity, the Routing Controller provides the Space/Ground Routing Managers with the routing-related configuration information they require to perform their functions. This information is computed ahead of time and provided to the LEO system management entity for distribution to the Routing Managers.
- *Space Routing Manager.* The Space Routing Manager executes actions and protocols as required in order to generate the control plane information needed by the IP forwarding function located within the spacecraft. Most of the control plane information and configuration logic is derived from information provided by the Routing Controller, but it also interacts with Ground Routing Managers on-ground to communicate non-nominal link interface related events and react upon unpredictable events.
- *Ground Routing Manager.* This element is similar to the Space Routing Manager, but for Ground Nodes. Most of the control plane information is derived from information provided by the Routing Controller, but it also interacts with Space Routing Managers to keep track of interface related events and to provide instructions to Space Routing Managers upon unpredictable events. Being a ground element, it can handle more information inputs from the Routing Controller and support a more complex logic.

E. Integration with AITRON

With the use case described in section III.A in mind, in terms of integration between AITRON and the described Routing Solution, we can consider two integration points. On one hand, the AITRON may be integrated with the Routing Controller for mid-to-long term strategic goals and administrative criteria, so that use of certain nodes or links is either encouraged or avoided. The AITRON accepts the routing strategies recommended by the Routing Controller as an input for the Network Topology Status Manager as a future operational topology. An example would be the need to avoid Ground Stations located in a certain country. On the other, assuming that the Routing Controller has configured several routing path options, the AITRON may interact with the Ground Routing Manager for selection in real time among the different options, with a more tactical viewpoint.

F. Verification approach and initial results

Concept verification is based on a specific test bed which builds upon the Mininet framework [3] and models the LEO satellite constellation. Each modelled satellite and ground node is executed as an independent container, with more than 250 containers running in parallel (Fig. 2). Use of containers allows evaluating performance with real applications and a more realistic prototyping of the solution components.

Tests use a very realistic network topology generated by a specific tool (derived from [4]). This tool forecasts the movement of the satellite constellation network based on the constellation parameters and calculates the inter-satellite link distance, the visibility between the GSs and the satellites (satellites in range) and the feeder link distance and, finally, generates a sequence of graph files representing the evolution of the interconnection of these elements, including the link delays. It also uses a contact planning algorithm to limit the GS to satellite links to the maximum number of GS and satellite antennas.

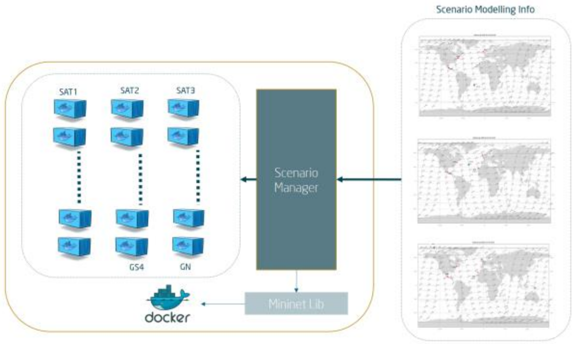

Fig. 2. Concept verification test bed – LEO constellation modelling

The test bed also allows replacing a container node by an external, physical node, e.g. a breadboard which supports the Space Routing Manager functionality, now running on a more resource-constrained device and on a specific Linux image compiled for an ARM64 processor architecture.

Initial results with prototypes for the Routing Solution elements show that the followed Software Defined Networking approach is satisfactory. Tests have shown that predictable GS and polar link changes can be handled by the Routing Solution without adding relevant jitter and causing any packet loss.

The failure recovery mechanisms work as expected and show a good compliance with performance requirements and a good margin even with very realistic topologies, which include predictable link changes in parallel to the unpredictable link interruptions and a high number of satellite nodes.

The next steps are to go deeper in the integration of the LEO satellite Routing Controller and Ground Routing Manager advanced prototypes with the AITRON and to experiment with different interface options and decision criteria.

IV. AITRON ROADMAP AND FUTURE DEVELOPMENTS

AITRON currently performs standard dynamic routing in a distributed way along with its own advanced cross-layer per-hop QoS policy prioritization to provide a first end-to-end QoS assurance approach.

As mentioned previously there are two key technologies that will condition future developments. Firstly, SDN technology accommodation to provide a centralized orchestration of the traffic to perform QoS based routing and load balancing to optimize the whole network resources. Secondly, predictive communications (with AI trained algorithms) to perform predictions at radio network status level and at network topology level as well to enhance a decision engine that allows to anticipate more constrained network resources topology and prevent packet loss. Within predictive communications scope, non-AI based future recommendations for routing decision provided by other external elements (like in the integration with LEO constellations) shall be integrated for an even better routing decision process.

These developments will have to be properly integrated so that the full power of these technologies can be maximized and the QoS of very heterogeneous traffic can be fulfilled, specially referring to safety critical real-time communication.

Finally, AITRON will address proper integration of wireless technologies that may become standard de-facto like 6G. Its targeted data rate speeds (about 1 terabit per second) and latency capabilities (microsecond range) will allow the use of new applications that requires the exchange of very large amount data and ultra-low delay transmission. AITRON will have to accommodate such capabilities along with other networks.

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