Terrestrial-Satellite Integration in Dynamic 5G Backhaul Networks

The SANSA Project Solution

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***Abstract*—This paper presents a dynamic backhaul network in order to face some of the main 5G challenges such as 100% coverage, improved capacity or reduction in energy consumption. The proposed solution, elaborated within the SANSA H2020 project, is based on the seamless integration of the satellite component in a terrestrial network capable of reconfiguring its topology according to the traffic demands. The paper highlights the benefits of this hybrid network and describes the technology enablers to bring it to the reality. Finally, the SANSA's network simulation framework based on ns3 is presented, jointly with a preliminary analysis of the routing and load balancing needs for a hybrid and dynamic network.**

Keywords—5G; terrestrial-satellite integration; dynamic backhaul; self-organized routing; load balancing

I. Introduction

The Fifth Generation of Mobile Communications (5G) is not seen as an evolution of existing 4G with increased capacity and data rates but as an integral communication network covering such diverse applications as very high throughput (4k real time video-conferences), very low latency (autonomous driving) and massive machine type communications (MTC), among others. Specifically, industry and academia have identified the following requirements for future 5G networks [1]: 1-10Gbps of throughput, 1ms end-to-end latency, 1000x capacity improvement, 10-100x number of connected devices, 99.999% availability, 100% coverage, 90% reduction in network energy consumption and up to ten year battery life for low power MTC devices. Several conclusions arise from the observation of these requirements. First, the satellite communications must be included as part of 5G as the only cost-affordable way for meeting the availability and coverage requirements. Second, not all applications supported by 5G will need to meet all requirements. Several international fora have combined these two issues for identifying a set of 5G use cases enabled by satcoms [2][3][4] which may be written as: areas difficult to be covered by terrestrial infrastructure, disaster relief, public safety, back up connections and multimedia distribution (Content Delivery Networks). Remarkably, these cases perfectly match some of the 5G use cases identified in [5], such as the 50Mbps everywhere or the ultra-low cost networks for low ARPU areas.

The third conclusion from the 5G requirements is that a change of paradigm is needed for 5G mobile backhaul networks. Currently, backhaul networks are static in the sense that they have fixed topologies based on fixed point-to-point (PTP) or point-to-multipoint (PTMP) links. An exhaustive radio planning is needed before deployment and new nodes cannot be easily added. In addition, the network can hardly react to link failures or congestion that have not been considered in advance. These limitations are not compatible with future 5G networks which will implement a massive cell densification and heterogeneous access technologies. Therefore, a dynamic solution capable of adapting the network to the traffic demands and of overcoming potential link failures will be a must. In this sense, dynamic network layer techniques such as centralized topology reconfiguration to minimize interference levels and distributed routing and load balancing solutions to provide fast reaction to dynamic events (e.g. sudden congestion) are likely to become of vital interest. A dynamic solution is also needed from the spectrum regulation point of view. Currently, spectrum coexistence between terrestrial and satellite components is scarcely considered what results in an underutilization of the resources. Moreover, on the

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terrestrial segment, the traditional per-link basis regulation does not allow dynamic reconfiguration of network topologies. This is being overcome by block spectrum licensing, which is being used in combination with PTMP links but still not fully covers dynamic PTP reconfiguration.

The aim of this paper is to detail the dynamic hybrid-terrestrial satellite backhaul network proposed in the H2020 SANSA (**S**hared **A**ccess Terrestrial-Satellite Backhaul **N**etwork enabled by **S**mart **A**ntennas) project [6], which deals with all the aforementioned issues. An overview of the solution envisaged in SANSA is described in Section II and the key enabling components to implement that solution are discussed in Section III. An initial analysis regarding routing and load balancing for the network layer is presented in Section IV. Finally, Section V concludes the paper.

II. The SANSA Concept for Dynamic Backhaul Networks

The objectives of the SANSA project are to improve the aggregated throughput and resilience against link failures or congestion of wireless backhaul networks, while reducing their energy consumption and assuring an efficient use of the scarce spectrum. In addition, SANSA also aims to facilitate the deployment of mobile networks in both low populated (or remote) and highly populated areas. The solution envisaged is a self-organizing backhaul network based on the three key principles elaborated next.

Firstly, a seamless integration of the satellite segment in terrestrial backhaul networks. By *seamless* here it must be understood that at the network layer, the satellite is treated just as another backhaul node with direct connection to the core network and with different physical layer features (delay, throughput, etc.). The integration of the satellite is the key enabler for meeting the desired 100% coverage of some of the 5G use cases such as the 50Mbps everywhere or the ultra-low cost networks for low ARPU areas. SANSA focuses on the use of high throughput multi-beam geostationary satellite systems.

Secondly, a terrestrial network capable of reconfiguring its topology according to the traffic demands. This reconfiguration is the basis of the dynamic behavior of the backhaul network, and thus the main enabler of the throughput and resilience improvement. However, the satellite integration also plays a key role here by providing a large set of redundant paths which may be used for offloading data in order to alleviate the capacity requirements of the terrestrial segment. In this sense, the satellite is not only used for coverage extension, but it also provides capacity and availability improvement in rural or early 5G deployments.

Fig. 1 exemplifies how the satellite and the terrestrial reconfiguration can be dynamically used to improve the performance of traditional low redundancy backhaul networks. The network reconfiguration solutions to each of the congestion events are:

- Event 1 (E1): Heavy congestion on the link B-C affects the traffic coming from Node A. Node A activates the satellite link for backhauling instead of forwarding the traffic to Node B, which decongest the link B-C.
- Event 2 (E2): Moderate congestion on the link D-G affects the traffic coming from Nodes A, B, C and E. In Node E part of the traffic is offloaded through the satellite link resulting in a reduction of the total traffic arriving at Node D. Subsequently the link D-G is decongested.
- Event 3 (E3): Heavy congestion on the link F-G affects the traffic coming from Nodes I, J and H. The terrestrial Node F creates a second link with Node E (F-E) so that the traffic from Node F is split between the links F-G and F-E. The traffic arriving at Node E is then backhauled through the satellite link of the node.
- Event 4 (E4): Moderate congestion on the link I-F affects the traffic coming from Nodes J and H. As the link I-F is starting to become congested, Node I offloads part of the traffic through the satellite link.

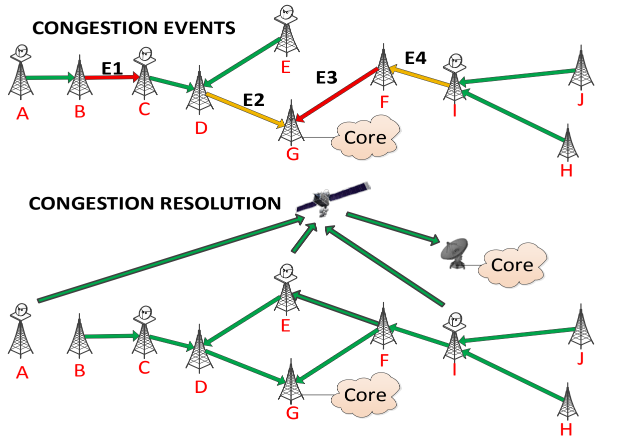

Fig. 1. Dynamic topology reconfiguration enabled by the satellite integration and the terrestrial reconfiguration capabilities.

The terrestrial reconfiguration provides also benefits in terms of cost of deployments and network energy consumption. On one side, it reduces the need for an exhaustive radio planning of the network which can reduce significantly the CAPEX of mobile operators. In addition, this reconfiguration is based on the use of smart antennas with self-pointing capabilities that eliminates the need of qualified personnel at installation. On the other side, the reconfiguration also allows setting some nodes in sleep mode during low-demand traffic periods resulting in important energy consumption savings.

The third key principle of the SANSA concept is the spectrum coexistence of satellite and terrestrial segments. The main idea is to use aggressive frequency reuse schemes between terrestrial links, and between terrestrial and satellite links in order to assure an efficient use of the available spectrum. The extended Ka band is considered since current regulation already allows some spectrum sharing in the downlink band [7]. In particular, uncoordinated satellite receivers can be deployed in the 17.7-19.7GHz band without claiming for protection from terrestrial transmitters. SANSA envisages that terrestrial and satellite operators can arrive to a kind of a licensed shared access agreement in which terrestrial nodes protect satellite receivers, and the last ones contribute to boost the performance of the network.

III. KEY ENABLING COMPONENTS

In order to deploy a hybrid and dynamic backhaul network, changes at all lower layers (from physical to network layer) of communications systems are needed. However, the challenge here is to keep these changes to the minimum in order to make the dynamic solution compatible with the traditional ones, and also for keeping the cost-network performance tradeoff in figures which could encourage the investments of network operators. The required solutions at the different layers are described next.

A. *Physical Layer (PHY)*

At the PHY layer, SANSA foresees the deployment of smart antennas at the terrestrial backhaul nodes. The objectives of these antennas are twofold. On the one hand, to enable spatial interference mitigation. Hence the smart antennas should be able to place radiation nulls on the directions of unintended terrestrial receivers and satellite receivers. The interference to the satellite receivers can be further mitigated by using some kind of side low canceller or beamforming solution at the satellite receiver too, but this is out of the scope of SANSA project.

On the other hand, the smart antennas must enable the terrestrial network topology reconfiguration. In this sense, different antenna operation modes have been identified, from a single reconfigurable beam (for PTP links), going to multiple reconfigurable beams (supporting several PTP links) to multicast multi-beam configurations (for PTMP configurations). The possibility of dynamically changing the mode of operation using the same antenna structure would infer a high reconfiguration capability to the network. However, there is a clear cost-beamforming performance tradeoff affecting this solution. Therefore SANSA is analyzing different cost–effective solutions such as hybrid analog-digital beamforming [11] and reconfigurable reflectarrays [12].

B. *Radio Resource Management (RRM)*

Radio resource management is a cross-layer activity of crucial importance for dynamic and hybrid backhaul networks. In traditional terrestrial wireless backhaul, the power and frequency assignment is handled at regulation level following a per-link basis scheme, which eliminated the need of complex RRM solutions. However, the dynamic reconfiguration considered here combined with an aggressive spectrum reuse, drastically increase the possibility of interferences which must be mitigated using novel cognitive, dynamic and hybrid RRM techniques. In addition, database assisted shared access can be used in order to eliminate the need of coordination of satellite receivers and to reduce the feedback overhead among terrestrial nodes. These database should contain the precise location of all network nodes and terrain data in order to assess the RRM interference mitigation techniques to be applied. The information on the databases can be extracted from regulatory bodies and refined by spectrum sensing.

The SANSA concept considers that the RRM algorithms run in a functional block called Radio Environment Mapping (REM) which give support to the network managers in the evaluation and selection of optimal network topologies, as further explained next.

C. *Network Layer*

A reconfigurable 5G all-wireless satellite-terrestrial backhaul not only requires of dynamic techniques at the PHY layer (smart antennas) and RRM techniques, but also dynamic techniques at the Network Layer. Furthermore, enabling reconfiguration dynamicity requires of an entity able to coordinate all the decisions. To attain a coordinated dynamicity, SANSA defines a primal entity referred to as the Hybrid Network Manager (HNM) in charge of coordinating all the reconfiguration backhaul decisions. The second main entity is referred to as the iBN (intelligent Backhaul Node), which is the entity enforcing the global network reconfiguration decisions taken by the HNM. It is important to note that this does not preclude the introduction of autonomous distributed decisions for network functions that require quick reactions (e.g., routing and load-balancing).

In what follows, we provide more detail of the iBN and HNM components.

1) *Intelligent Backhaul Node*

The iBN extends the internal architecture of traditional BNs introducing terrestrial dynamic beamforming and satellite connection together with new functional blocks. These building blocks are autonomous, and are able to take decisions based on the backhaul topology re-configurations provided by the HNM. Amongst these new functions, the iBN will embed:

a) Intelligent Routing and Load Balancing: This function includes the routing algorithm and is in charge of distributing the traffic through the multi-hop wireless backhaul network contemplated in SANSA. In particular, we will provide in next section an initial analysis of the implications of using static routing and load balancing policies.

b) Traffic Classification: This function is in charge of determining the mapping of traffic flows to the backhaul resources used to transport them. For example, it assures that only delay tolerant traffic is routed through the satellite.

c) Energy Efficiency: This function is in charge of controlling access and backhaul energy consumption, therefore reducing operator's OPEX while satisfying traffic demands. In particular it can activate/deactivate access and/or backhaul interfaces depending on the traffic loads.

A representation of the different components embedded in the iBN can be shown in Fig. 2.

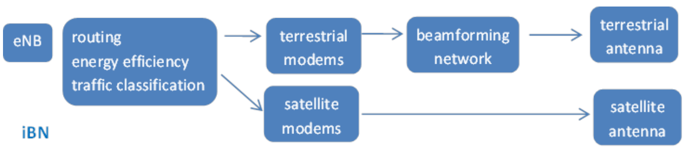

Fig. 2. Intelligent Backhaul Node Architecture

Finally, note that the aforementioned functions in the iBNs perform network decisions on a short (e.g. intelligent routing and traffic classification) and medium (e.g. energy efficiency) time-scale basis.

2) *Hybrid Network Manager*

The HNM is a new entity introduced by SANSA in charge of configuring the topology formed between the iBNs and managing the satellite resources. The HNM is the central element of SANSA that aggregates all the network resources and performs long and medium time-scale configuration changes.

According to Fig. 3, this manager includes the following main modules:

a) Events management: This component monitors the network in order to detect any state change (node interface switch on/off), or a link failure (based on modem monitored SNR values), or even a congestion situation (based on traffic level). When a network change is detected, the HNM must propose topology changes.

b) Topology management: The HNM must give an efficient response to any interoperability issue, diagnosing network problems or new load demands and must evolve the network topology. Therefore, this component performs topology calculations to restore the network upon certain networking (reconfiguration) events. As input, it receives new network states from the Events management component, and produces candidate topologies that are pre-validated by the REM functional block. Indeed, the REM function calculates interference levels and performs the carrier and power allocation for these candidate topologies. Then, the optimal topology is selected based on performance figures calculated from the REM output data (i.e. spectrum efficiency, iBN throughput, network capacity, etc.). Finally the new topology is forwarded to the Configuration management component.

c) Configuration management: This component is in charge of reconfiguring the iBNs in the network according to the new topology. Also, it is used for managing the satellite resources interfacing with the Satellite Ground Segment.

With the aforementioned modules, the HNM is able to configure bot satellite and terrestrial resources. In Fig. 4, we reveal how external interfaces provided by the HNM configure the topology in the terrestrial and satellite ground segments, based on two main sources of information. First, the interference levels provided by the REM. Second, iBN messages in the form of alarms and events (e.g., link flap event) directly communicated to the HNM that can cause significant changes in the overall performance of the network and hence require the intervention of the HNM.

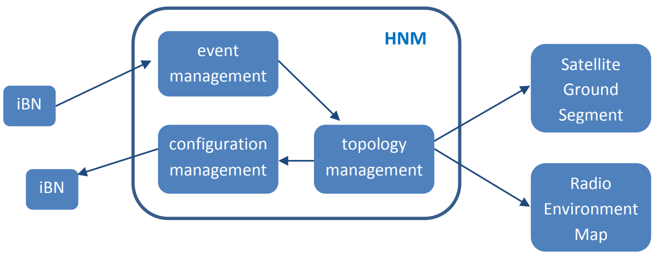

Fig. 3. Hybrid Network Manager Architecture

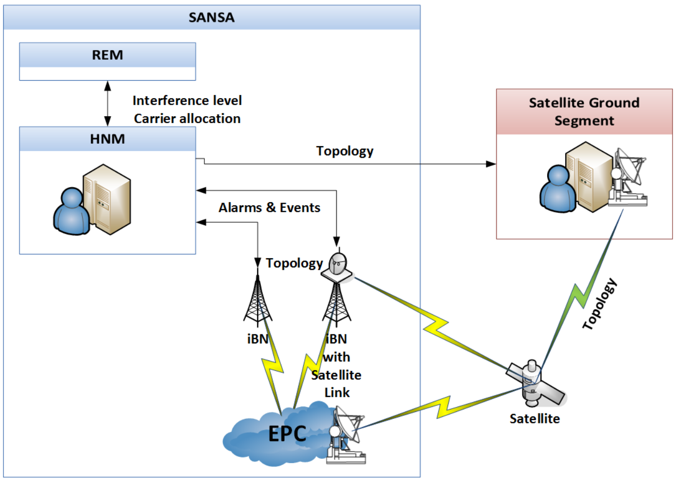

Fig. 4. Hybrid Network Manager External Interfaces

IV. THE NECESSITY OF DYNAMICITY: THE CASE OF ROUTING AND LOAD BALANCING

As explained in previous sections, SANSA proposes to enable dynamicity at several building blocks located at different layers (PHY, NET) in the network stack. In this section, we are presenting the necessity of introducing such dynamicity for the routing and load balancing function embedded in the iBNs presented in previous section. In particular, this section justifies the need of a dynamic routing and load balancing distributed over all the iBNs in the network to conduct quick routing decisions without the intervention of the HNM, in charge of reconfiguring other aspects, such as the topology. Thus, the goal of this section is two-fold: 1) to motivate the use of dynamic routing and load balancing strategies in contrast to static routing and load balancing policies, and 2) to show the proper operation of the simulation framework developed in SANSA.

A. *Simulation Methodology*

We have used ns-3 [8] as basis for the simulation framework. Additionally, ns-3 framework counts with the Lena (LTE-EPC Network Simulator) module [9], developed at CTTC. This module consists of an accurate model of the LTE/EPC protocol stack useful for modeling LTE access and the core network. As indicated by Fig. 5, the simulated hybrid backhaul scenario is a 2x3 grid mesh network formed by the iBNs in which some nodes (i.e., nodes 2, 4, and 5) count with a satellite link to directly reach the EPC.

Note also that certain terrestrial nodes (i.e., node 3) in Fig. 5 can directly reach the EPC through a terrestrial link. The rate of the satellite link modelled in ns-3 is of 300Mbps and propagation delay is of 250ms. The rate of the terrestrial links is of 11Mbps and the propagation delay is of 10ms. User equipment are attached to any of the iBNs.

We conducted two different set of experiments and evaluated the attained throughput and latencies of the network. In the first experiment, a UE attached to iBN1 generates an uplink TCP flow (i.e., Flow 1). The static routing and load balancing algorithm in iBN1 determines to use the shortest path determined by mesh terrestrial backhaul. While this TCP flow is still traversing the terrestrial backhaul, a new uplink TCP flow (Flow2 in Fig. 6) generated by the very same UE joins the hybrid backhaul network. The iBN1 including a static routing and load balancing policy determines to change the backhaul medium of Flow1 to the satellite backhaul (through iBN2), while Flow2 reaches the EPC using an only-terrestrial path (the same used by Flow1). Consequently, uplink TCP Flow1 uses a hybrid terrestrial-satellite backhaul to reach the EPC. It is important to note that downlink signaling traffic is using the equivalent path. In the second case, we scale the number of UEs so that there is a UE attached to each iBN in the 2x3 grid mesh backhaul network. The static routing and load balancing algorithm embedded in each iBN determines the following simple heuristic: half of the traffic arriving to the iBN is mapped to reach the EPC using the satellite backhaul, while the rest of the traffic reaches the EPC using only the terrestrial resources. The aim of this experiment is to see the impact on the network performance when adding progressively resources, such as new satellite terminals (STs) (from zero to five) and when changing the number of iBN nodes connected to the EPC (from one to two). Notice that in this experiment, an iBN counting with connection to the EPC cannot be equipped with a ST. Traffic is generated to achieve network saturation conditions.

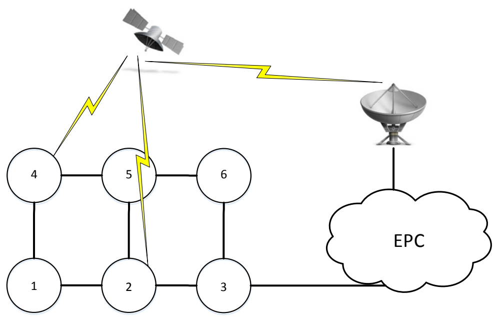

Fig. 5. Simulation scenario modelling six iBNs and a GEO satellite used as backhaul between the small cells and the EPC.

B. *Latency results*

In the first experiment we can observe the sudden change of latency experienced by the Flow1 (see Fig. 6). This is due to the fact that TCP Flow1 is routed through the satellite backhaul instead of reaching the EPC by traversing the terrestrial network. In particular, latency increases from around 30ms to 260ms.

Note that the propagation delay introduced by the satellite node is of 250ms. Flow2 joining the network at instant 15 in the simulation experiences the latency to that experienced by Flow1. In this sense, simulation results confirm the proper operation of the satellite node modelled in ns-3 and the terrestrial mesh backhaul in terms of delay.

In the second analyzed scenario, we observe how the number of terrestrial iBNs including a terrestrial connection to the EPC significantly influences the attained latency. Though intuitively the achieved latency of the network should decrease with the number of direct (1-hop) terrestrial connections, attained latency highly varies irrespectively of the number of 1-hop terrestrial connections. Again, latency results also confirm that to properly exploit backhaul resources it is needed a dynamic routing protocol. This misuse of satellite resources is due to 1) the static traffic management policy and 2) the deployment of satellite link in a non-congested zone. Furthermore, Fig. 7 reveals that more resources could even translate into latency degradation. This is the case of introducing a single ST in the network. Both the satellite backhaul network and the allocation of terrestrial resources to reach the satellite backhaul get congested due to this static traffic management policy.

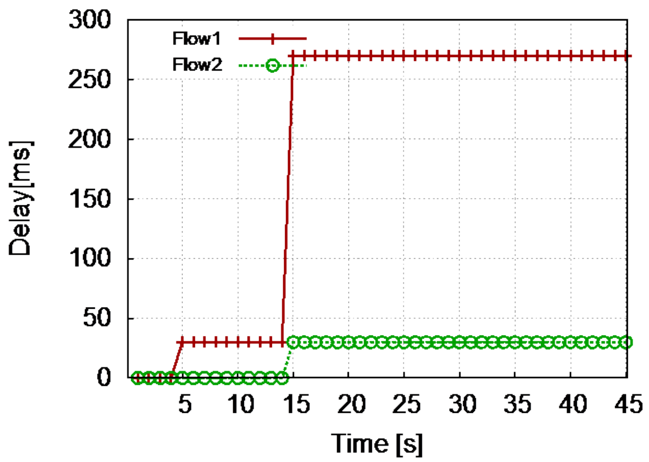

Fig. 6. Latency attained by two TCP flows. Flow2 has priority over Flow1. Flow1 is routed over the satellite backhaul when Flow2 starts. The TCP connection of Flow1 is maintained during the whole experiment.

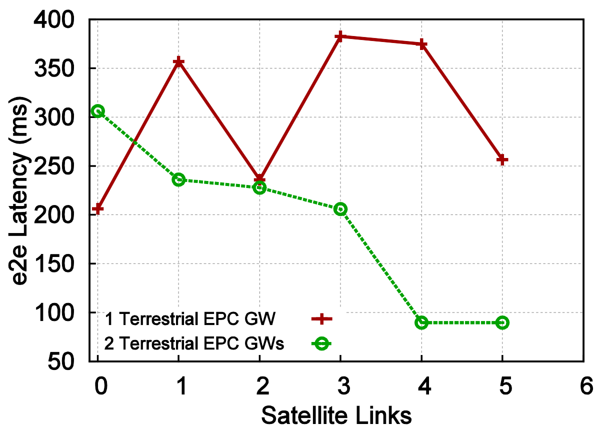

Fig. 7. Latency attained with the increase of the number of satellite and terrestrial resources. Static routing and load balancing avoids the exploitation of backhaul resources.

C. *Throughput Results*

Fig. 8 illustrates the performance of a TCP flow when changing the backhaul medium to reach the EPC. In particular, it shows the evolution of the throughput experienced by these flows when using Hybla TCP variant [10] . We can notice how the satellite backhaul degrades the performance of Flow1 when routed over the satellite resource, while Flow2, routed over the terrestrial network, can achieve the injected throughput. The sudden increase in round trip time (RTT) of Flow1 (around

500ms) causes retransmission time outs (RTO), which lead to an abrupt decrease of the attained throughput. An important observation is that the connectivity of Flow1 is not lost while switching to the satellite backhaul. In fact, Flow1 reaches 90% of its injected throughput after 25 seconds. In this sense, we can conclude that TCP flows without strict requirements of throughput and delay can be seamlessly transported through the satellite backhaul.

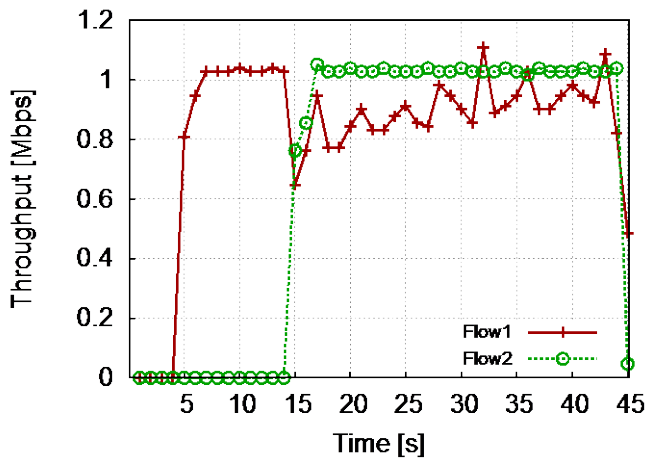

Fig. 8. Throughput attained by two TCP flows. Flow2 has priority over Flow1. Flow1 is routed over the satellite backhaul when Flow2 starts. The TCP connection of Flow1 is maintained during the whole experiment.

In the second experiment, 0 indicates that though the attained throughput grows with the number of satellite links, this is not always the case. For instance, we observed that the inclusion of satellite link can even degrade the attained throughput. This is due to the fact of the static design of the routing and load balancing algorithm, always splitting half the traffic though the satellite backhaul no matter the location in the mesh network of such links, and the other half through the terrestrial backhaul.

TABLE 1. Throughput gains with a static routing and load balancing algorithm. This illustrates a misuse of satellite resource, hence justifying the necessity of self-organized routing and load balancing policies.

Number of Satellite Links	**Throughput Gains**
0	x
1	0.97x
2	1.25x
3	1.26x
4	1.325x

D. Observations

A routing and load balancing scheme requires of dynamic capabilities to better decide on-the-fly the more proper allocation of traffic to the hybrid backhaul proposed in SANSA. Thus, this is one of the main contributions that SANSA seeks at the network level: to design a proper dynamic routing and load balancing protocol to properly react and adapt to sudden changes in traffic demands, and topology reconfigurations yield by the HNM.

V. Conclusions

This paper presented the SANSA answer to the requirements of 5G backhaul networks in terms of capacity, coverage, energy consumption and deployment costs. The SANSA solution is based on a hybrid terrestrial satellite backhaul in which the satellite not only provides extended coverage but also the possibility of alleviating the terrestrial congestion by offloading traffic through it. The combination of this feature with a terrestrial network capable of adapting its topology to the traffic needs results in a dynamic solution which will boost the performance of future networks.

The SANSA project foresees that the implementation of such solution requires the deployment of low cost smart antennas at the backhaul nodes, the use of dynamic and hybrid radio resource management techniques and a novel hybrid network management scheme based on two entities: a decentralized one managing network topology reconfiguration (hybrid network manager) and a distributed one implementing dynamic routing and load balancing (intelligent backhaul node). A simulation framework based on ns-3 for analyzing the hybrid network has been presented and validated, and preliminary results strongly support the need of using dynamic routing and load balancing strategies in order to efficiently use all the network resources, being them terrestrial or satellite.

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