Evaluation of Hybrid Terrestrial-satellite Suburban Wireless Mesh Backhauls for LTE networks

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***Abstract*—The development of 5G networks supposes a big challenge for mobile operators in order to satisfy the ambitious objective of delivering broadband services ubiquitously. Based on this, the increasing capabilities of satellite systems have created the consensus that such systems can satisfy the required necessities for several scenarios, such as for rural or low-density populated areas. Used in combination with a terrestrial wireless backhaul, satellite backhauls are envisaged as a solution to improve the network efficiency in terms of delivered traffic to access nodes while increasing its resiliency for the mentioned scenarios. This paper presents i) our ns-3 framework for modeling hybrid terrestrial-satellite mesh backhaul networks that carry LTE traffic and ii) a comparison of our different backpressure-based approaches against generic shortest-path routing in a low-density suburban scenario for LTE networks. Simulation results reveal the advantages of backpressure-based approaches to make an efficient use of the network resources while integrating seamlessly both terrestrial and satellite backhaul resources.**

I. Introduction

The development of 5G networks is addressing very ambitious Key Performance Indicators (KPIs) in terms of overall/per user capacity and latency while requiring the provision of broadband services ubiquitously. Differently to previous mobile network generations, 5G is not only the redefinition of the physical layer but also entails the cooperation between different radio technologies in the different network segments (access, backhaul) to achieve the delivery of services at the requested level of performance. This fact, together with the recent technological advances in satellite communication, bringing high capacity links while reducing the price per bit, is causing a revisit of the role of satellite communications in 5G networks [1]. Specifically, the seamless integration of satellite resources into mobile networks is of capital interest for several reasons such as mobile service extension for rural or low-dense populated scenarios, increased backhaul network resiliency or traffic offloading. In parallel, terrestrial backhaul networks will have to evolve, being very unlikely to count with a fiber connection to reach each base station. A novel idea is to deploy networks of Small Cells (SCs) that can be meshed together by means of multiple wireless backhaul transport technologies (e.g., microwave or mmWave) that can provide path redundancy between the LTE access and the Evolved Packet Core (EPC). In this way, user and control plane traffic can be transported from/towards the EPC, with substantial benefits in terms of cost, deployment flexibility, coverage, and capacity combining both satellite and terrestrial backhaul resources.

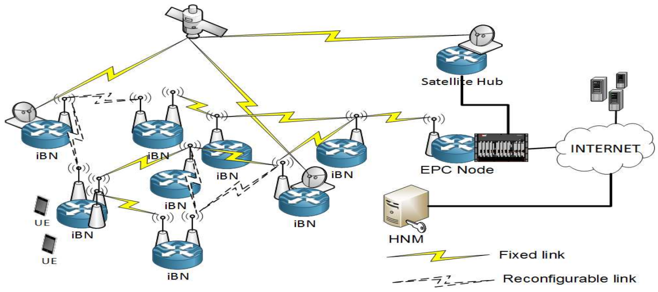

Fig. 1: Hybrid Terrestrial-Satellite wireless mesh backhaul network proposed in SANSA

Consequently, both types of network resources, terrestrial and satellite, will have to cooperate efficiently in order to satisfy 5G service requirements. Moreover, the path redundancy offered by this new kind of hybrid wireless mesh networks puts emphasis on the routing protocol abilities to exploit this redundancy. In such context, the EU H2020 SANSA project [3] proposes a self-reconfigurable hybrid terrestrial-satellite backhaul network as an answer to these challenges, as depicted in Figure 1. This network is based on three key principles: (i) a seamless integration of the satellite backhaul component into the terrestrial backhaul network, (ii) a terrestrial wireless backhaul network capable of reconfiguring its topology according to the needs of the network (traffic demands, link failures, energy consumption) and (iii) a shared spectrum between satellite and terrestrial segments.

Currently, the scope of this paper is focused at the networking level of the first objective mentioned before. In particular, this work presents a flexible simulation framework based on the ns-3 network simulator [4], which integrates the required elements defined in the SANSA architecture and which is able to simulate the access, the core and complex and custom backhaul network segments of a hybrid terrestrial-satellite mobile network. Additionally, in this paper we also present a performance evaluation of TCP and UDP connections in a scenario modeling a suburban area in Finnland. In particular, we focus on i) the response of different backhaul routing protocols based on their granularity taking forwarding decisions and ii) the degree of backhaul traffic offload through the satellite backhaul segment. Between the evaluated routing protocols, this work considers the comparison of our backpressure-based approach called Backpressure for Multi-radio (BP-MR) [6], [13] embedding the balance of traffic at the per-flow level and the per-packet level with respect to State of the Art (SoA) shortest-path based routing approaches [7].

The remainder of this paper is organised as follows. Section II presents how the network simulator ns-3 has been extended to be able to simulate the envisaged scenarios defined in the SANSA project in terms of topology and reconfiguration capabilities according to network events. Section III provides the necessary background on *BP-MR*, our proposed backhaul routing approach. Section IV presents the conducted performance evaluation in the Finnland suburban scenario considered in the SANSA project. Section V covers related work and Section VI concludes the paper.

II. Modeling a Flexible Hybrid Mesh Backhaul for Mobile Network

The proposed simulation framework is based on ns-3 [4], a modular discrete-event network simulator, and more specifically on LENA module, a LTE radio access and EPC simulator [5]. This section presents different aspects of how ns-3/LENA simulator has been extended to simulate the transport network architecture (TNA) proposed at SANSA project integrating seamlessly terrestrial and satellite resources to transport LTE traffic between the User Equipment (UE) and the EPC as detailed in [3].

A. Modeling the wireless backhaul Transport Network Layer

1) Intelligent Backhaul Nodes (iBN): A key element of the proposed TNA is the intelligent Backhaul Node (iBN) featuring distributed traffic offloading function towards the satellite segment and a distributed backhaul routing function operating on top of self-reconfigurable terrestrial and satellite backhaul interfaces. In particular, each iBN can be equipped with multiple transport interfaces emulating wireless terrestrial links (i.e., microwave or mmWave) and some of them can be equipped with an interface emulating a Satellite Terminal (ST). The iBNs embed an eNodeB (eNB) to provide access capabilities to UEs and are in charge of forwarding the traffic towards/from the EPC to the corresponding UE using the mentioned transport interfaces ruled by the installed traffic offloading and distributed routing functions to balance traffic load through the available network resources. Note that since not all iBNs may endow a ST, a traffic flow determined to use satellite resources uses terrestrial backhaul resources to eventually reach an iBN/s that is equipped with a ST.

2) Satellite Network: In SANSA, the satellite network is seen as an element offering a reliable and almost ubiquitous communication channel for the iBNs whose main functionality is to provide additional transport capability to iBNs equipped with STs as well as to increase network resiliency. In this framework, the satellite network has been modelled as a single entity which comprises the satellite hub, connected on one side to the EPC by means of a wired connection and the satellite itself, which connects the iBNs to the satellite hub. As the objective of this framework is to test network layer techniques, the satellite link has been modelled as a point-to-point link with a certain transmission rate, packet error rate and a propagation delay corresponding to a GEO satellite (in the order of 250ms). It is important to note that not all the iBNs in the backhaul network may endow a ST to not incur in an excessive increase of CAPEX expenditures.

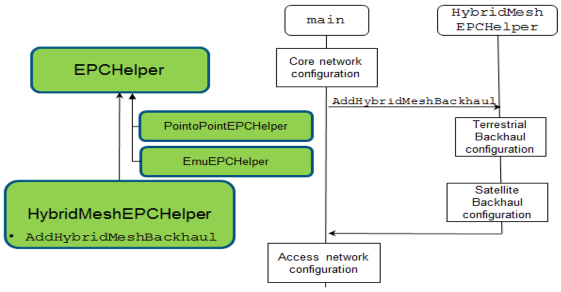

Fig. 2: LENA extensions to support Hybrid Satellite-Terrestrial mesh backhaul mobile network

B. Connecting the Transport Network Layer to the Mobile Network Layer

LENA [5] models both the RAN (i.e., the eNB and UE) and the Core (i.e, EPC) of an LTE network, not supporting a backhaul infrastructure more complex than a single wired cable between each defined eNB and the EPC. The proposed extension consists of a flexible API detailed in the form of a new class called `HybridMeshEPCHelper`, extending the `EPCHelper` class to interconnect the access and the core network segment through the defined custom backhaul network. The most important method defined in this new class is `AddHybridMeshBackhaul`, which is dedicated to build and configure the hybrid backhaul network (network topology and characteristics of the terrestrial and satellite backhaul links) according to the configuration provided by the Hybrid Network Manager (HNM), the other key element of the TNA developed within the SANSA project. Figure 2 illustrates the developed LENA extensions and sequence diagram illustrating the configuration of the hybrid backhaul network.

C. Configuration capabilities of the Hybrid Backhaul Network

In the SANSA system, the HNM is a new proposed entity which includes functionalities to manage satellite and terrestrial backhaul resources. Based on global network information view obtained through network monitoring, the HNM is in charge of configuring the topology formed between the iBN nodes and the satellite resources, operating on long/medium timescales. In the presented framework, the HNM functionality is simulated by means of input parameter files and simulator events. In particular, the presented framework requires the following information to configure the backhaul network: i) topological matrix indicating how iBN are connected between them and the possible link states to simulate the behavior of smart antennas, ii) topological matrix indicating the link rate of the connected nodes, and iii) boolean vectors informing of the iBN connections to EPC and to the satellite network. Possible link states are: fixed link between nodes, activated/deactived smart link. Then, the behavior of the HNM is simulated by feeding simulation events and the proper configuration files to the framework at the required time. As mentioned before, currently, the scope of this paper is limited to the seamless integration of terrestrial and satellite resources, leaving reconfigurability experimentation for future work.

III. BP-MR BACKGROUND

BP-MR [6] is based on the Lyapunov-drift-plus penalty approach proposed by Neely [10], where routing decisions are taken distributively at each node on a per-packet basis combining queue backlog information (Lyapunov drift) with geographic information (penalty component). The relative importance of each component is adjusted dynamically by means of a parameter that finds the best trade-off between congestion avoidance and path length. The design of *BP-MR* started with the necessity of extending the operation and mitigate the inefficiencies of *BP* [20], a decentralized flavor of the original backpressure algorithm [9], towards routing LTE traffic (TCP and UDP) through heterogeneus wireless backhauls technologies forming sparse backhauls. To tackle sparse backhauls, Backpressure for Sparse Deployments (*BS*) [21] added a penalty function able to overcome dead ends in a scalable and decentralized way. However, *BS* was designed to tackle sparse topologies where nodes are equipped with a single backhaul radio but presented high inefficiencies in hybrid multi-radio backhaul deployments transporting TCP and UDP traffic.

Specifically, *BP-MR* takes dynamic routing decisions following a two-stage process. Firstly, it classifies data packets in a per-interface queue system according to their final destination. Secondly, it employs geographic and congestion information to compute the best possible next-hop, on a *per-packet* basis, from all possible forwarding options in each multi-radio backhaul node. Congestion information is obtained through the periodical exchange of control packets called HELLO. The per-interface queue system presents lower complexity and a better delay performance than the original per-flow queuing system [9], and its distributed routing decision feature contribute to its scalability and applicability capabilities.

However, these routing decisions on a *per-packet* basis may spread packets belonging to the same flow over many paths, being received out-of-order by the end point, creating a problem for the TCP receiver. In order to overcome the packet reordering problem, without losing the capability of *BP-MR* to circumvent congested paths, we proposed in [13] the *per-flow* path selection strategy to *BP-MR*. Through identifying a flow as an origin to destination stream of a transport layer connection between two end-hosts, each node maintains active per-flow state information, mapping the packets of a flow to its determined path, calculated the first time the node sees the flow. Nonetheless, a new flow has the flexibility to route dynamically to any of the available paths, and so is able to circumvent congested routes, without actually causing packet reordering at the destination.

IV. PERFORMANCE EVALUATION

A. Suburban Scenario Description and Methodology

We used as reference scenario the current deployment located in the suburban area of Helsinki in Finnland, which is detailed in [3]. The scenario in question covers a region of 17 Km^2 to serve a quite sparse population, a typical characteristic of suburban and rural environments. The original backhaul topology is comprised by fifteen transport nodes interconnected through bidirectional terrestrial links forming several star topologies operating in the 28 GHz band.

We modelled and augmented this reference topology using LENA by replacing legacy nodes by iBNs and including satellite and more terrestrial links to cope with the huge traffic surges also expected for upcoming 5G suburban deployments (see red lines in Figure 3). The transport nodes count with several point-to-point (PTP) interfaces, whose link rate is derived from an interference analysis and the characteristics of the OptiX RTN 905 1E/2E Radio Transmission System detailed in [14]. Based on the experienced Signal-to-Interference Noise ratio (SINR), and when transmitting with a channel bandwidth of 28 MHz, data links at the different nodes are set from 135 Mbps to 210 Mbps. Additionally, each link is configured with 2 ms of delay accounting for propagation and iBN processing times. The queue sizes of the different iBN interfaces are set to 140 packets to respect the bandwidth-delay product criteria to reduce the default buffer size. Moreover, this network counts with two satellite connections placed at iBN number #4 and #12, whose forward link rate is set to 80 Mbps. The return link is set to 8 Mbps, with a delay of 250 ms and a Packet Error Rate (PER) of 10^{-4}. Configuration parameters for satellite connection have been also derived from [14].

The LTE Evolved Packet Core (EPC) connects to the backhaul both through terrestrial and satellite links. We configured a single wired connection to the EPC of 1 Gbps of capacity and 0.5 ms of delay in iBN number #8. The satellite ground station is connected to the EPC with a 1 Gbps and 0.5 ms of capacity and latency, respectively. The EPC modelled using LENA is connected to the Internet using a wired link featuring 10 Gbps of capacity and 5 ms of delay. As for the Radio Access Network (RAN), we configured LTE European frequencies and the Okumura-Hata propagation model [15].

We analyze the performance attained by LTE TCP traffic flows by measuring download finish time and Round Trip Time (RTT) and LTE UDP traffic flows by using throughput and latency under different backhaul routing approaches. In particular, we compare *per-packet* and the *per-flow* variants of *BP-MR* and Optimized Link State Routing (OLSR, RFC 3626), which has been extended to perform proper routing actions based on the satellite-terrestrial traffic split mentioned next. The latter, for the purpose of this paper, models the behavior of canonical transport protocols such as MPLS [7]. Simulation results consider several satellite-terrestrial traffic

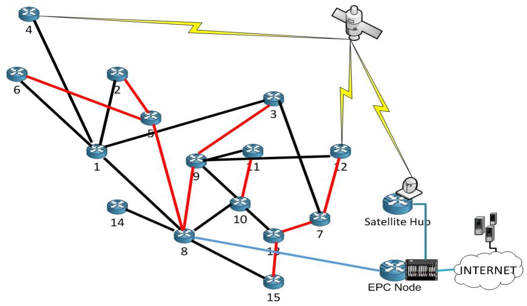

Fig. 3: Suburban Scenario under evaluation

split options: 0%, 5%, 10% and 15% of the traffic enters the backhaul network through the satellite connections, the rest through the terrestrial connection to the EPC. These traffic split values cover the cases spanning from no satellite traffic at all (i.e. 0%) to almost the limit point of the satellite connection (i.e. 15%) attending to the UDP experimentation explained later on. The reported values represented in boxes show the statistical distribution from the 25^{th} to the 75^{th} percentiles, and the whiskers from the 5^{th} to the 95^{th} percentiles. The marker represents the average value. In all simulations, each iBN has attached 4 UEs.

B. TCP evaluation

We modeled a 1MB file transfer from a remote server in the Internet to all the different UEs attached to iBNs, for a total of 60 TCP flows in each simulation. We considered the default and hugely used congestion control algorithm referred to as TCP Cubic [16]. Figure 4 shows the statistical distribution of the values of the experienced per-packet RTT and the finish download time of the terrestrial(up)/satellite(down) flows for the considered traffic splits.

As it can be observed for the terrestrial traffic, *per-packet* options presents higher values (average and wider whiskers) of RTT and finish download time among all the other considered routing variants. This is explained due to its strategy of taking routing decisions which may drive packets belonging to the same flow through different paths. On the other hand, *per-flow* strategy obtains better average values of the finish download time for the different traffic split in comparison to OLSR, due to its ability to still exploit the redundancy in the network without suffering from performance degradation due to out-of-order packet reception. This also yields in a better fairness between flows as revealed by the width of the whiskers. For the satellite traffic, results indicate that the RTT is dominated by the propagation delay of the satellite. This dominating effect is translated into the finish download time, where *per-flow* and OLSR present very similar performance. Moreover, this high propagation delay value is increasing the performance degradation, in terms of finish download time, experienced by *per-packet* due to its packet distribution approach in combination with TCP protocol.

C. UDP evaluation

We consider UDP Constant Bit Rate (CBR) downlink traffic of intensity 57.6 Mbps for each iBN distributed equally into its attached UEs according to the model guidelines proposed by EU EARTH project [11]. This value of traffic corresponds to the peak value of the daily traffic profile defined in [11] when considering half UEs as heavy users (their aggregated data volume is 300Mbps) and the other half as ordinary users (their aggregated data volume is 60Mbps). Figure 5 shows the statistical distribution of the experienced packet delay values and the average throughput of the terrestrial(up)/satellite(down) flows for the considered traffic splits.

We can see a complete opposite behavior with respect to the TCP case. The connectionless nature of UDP makes the *per-packet* approach the most suitable routing approach in terms of both latency and throughput because its approach allows an even network resource usage. When all traffic goes through the terrestrial backhaul (case 0%), OLSR experiences high delay values associated to long queuing. Additionally, OLSR experiences queue overflow attending to its value of packet delivery ratio (PDR), although having enough aggregated network resources, as shown by *BP-MR* approaches. On the other hand, the *per-flow* approach suffers the worse delay but achieves almost a 100% of PDR. As the traffic decreases in the terrestrial backhaul, the *per-flow* approach increases its performance, equaling the performance of *per-packet* thanks to its capacity to manage congestion on a per-flow basis. However, even OLSR, increases slightly its performance in terms of PDR, there is still queue overflows and the distribution of the delay value keeps similar, produced by long queueing times derived from its congestion unawareness and its static approach to route traffic between endpoints. For the satellite case, we can observe how the delay values are half the values experienced by TCP protocol because UDP is only accounting for one way. In this case, both the *per-flow* and the *per-packet* approaches obtain the same performance, being OLSR the one presenting a different trend due to the reasons mentioned previously. This is specially remarkable for the case when the satellite segment is transporting more traffic, that is, for the case 15%. In that case, latencies and overflows due to queuing appear as revealed by the values of PDR, throughput and delay distributions, while *BP-MR* is able to keep its performance due to its traffic distribution capabilities.

V. Related work

The first subsection reviews related work on modeling hybrid satellite-terrestrial networks whereas the second subsection provides related work in backhaul routing protocols.

A. Hybrid Satellite-Terrestrial Networks

The concept of integral communication network covering diverse applications proposed by 5G is provoking an increasing role of satellite networks thanks to the evolution of its capabilities. In the literature, one may find several examples of the integration of terrestrial and satellite networks, defining different kind of hybrid network architectures. For instance, [17] proposes a hybrid network architecture at the RAN segment, where the satellite channel is offered as an alternative access interfaces for the mobile user. Authors from [18],

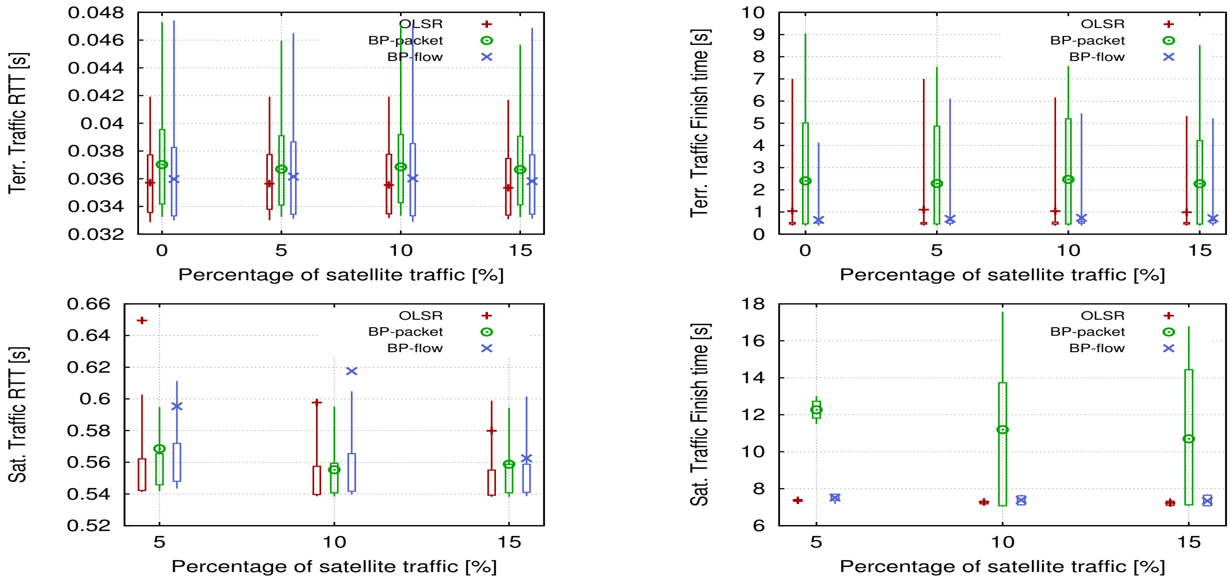

Fig. 4: RTT and Finish download time of terrestrial(up)/satellite(down) traffic for different splits using TCP transport protocol

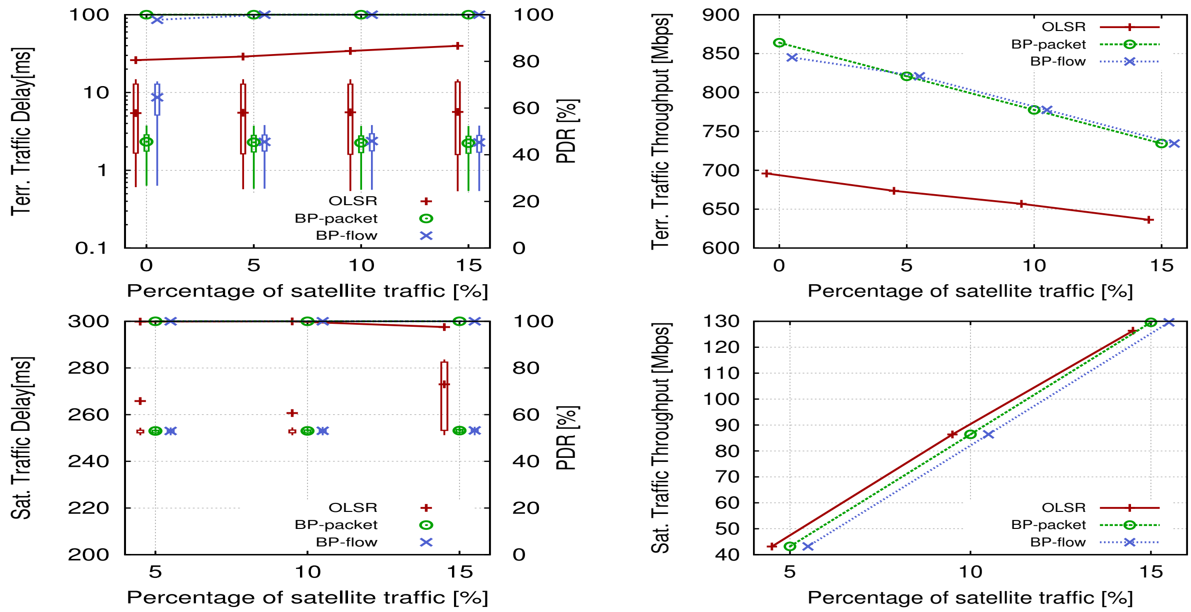

Fig. 5: Delay and throughput of terrestrial(up)/satellite(down) traffic for different splits using UDP transport protocol

propose a hybrid network using the satellite as the backhaul link required to provide coverage extension for rural areas. Similarly in [13], a satellite network is used to transport the backhauled traffic by a terrestrial wireless mesh network for the purpose of Public Protection and Disaster Relief (PPDR) services. The BATS projects [12], proposes to use an hybrid architecture but for the case of complementing fixed access services, such as ADSL, in rural environment. However, these proposals do not consider complex backhaul topologies seamlessly integrating terrestrial and satellite resources as the one proposed within this work, hence making its simulation challenging. In parallel to this work, there is an ongoing development of an open-source simulator for satellite networks based on ns-3 called sns3 [19]. Nonetheless, sns3 is focused in the physical modeling details of the satellite segment whereas in this work we opt for an abstraction of such physical level details to show the behaviour of network layer techniques under scalable hybrid wireless mesh backhaul with multiple satellite links.

B. Backhaul Routing Protocols

Regarding backhaul routing protocols, the present redundancy and the different types of resources in the proposed hybrid backhaul networks condition the definition of a suitable routing protocol to make a seamlessly and effective use of both types of resources (satellite and terrestrial). In this way, backhaul routing protocols need to exploit the different kind of resources by means of offering load balancing capabilities. Within this context, single path routing approaches that use metrics such as hop number, which would be the case of SoA backhaul routing approaches, may yield into inefficiencies due to the misuse of backhaul resources. A representative protocol with the aforementioned characteristics is that referred to as Multiprotocol Label Switching protocol (MPLS, RFC 5921) [7], which in the absence of node or link failures determines a static single path between endpoints. Such an strategy, designed for specific fiber-based backhaul deployments can misuse the existing path redundancy offered by hybrid backhauls. Thus, the expected path redundancy in hybrid satellite-terrestrial wireless backhauls puts emphasis on the routing protocol ability to exploit this redundancy for balancing the traffic load.

In this sense, backpressure-based approaches [8] offers, in theory, the possibility to exploit all available network resources, which is one of the main operator wishes, by dynamically mapping the trajectory followed by each data packet to the most underutilized path. The origins of the backpressure concept lies on the seminal paper of Tassiulas and Ephremides [9]. The root concept consists in a centralized policy which routes traffic in a multi-hop network by minimizing the Lyapunov drift in the network, that is, minimizing the sum of the queue *backlog*s in the network amongst time slots. Basically, defining as *backlog* the queue size at nodes, the main idea of backpressure is to give priority to links and paths that have higher differential *backlog* between neighbor nodes. Despite the throughput optimality promise, this work presents several limitations, such as centralized control mode, high queuing complexity due to the maintenance of a per-flow queueing system, and poor delay performance. Recently, many proposals have been presented to alleviate the effect of these issues [8], being *BP-MR* [6] one of them.

VI. Conclusions

This paper presents a flexible simulation framework based on ns-3 for modeling and conducting performance evaluations of self-reconfigurable hybrid terrestrial-satellite backhaul networks for 5G networks. This framework has been used to model a reference rural scenario defined within the EU SANSA project [3] and to evaluate different backhaul routing protocols. In particular, we evaluate *BP-MR per-flow* and *BP-MR per-packet*, whose objective is to make a seamless integration of both types of resources while exploiting the path redundancy offered by the hybrid backhaul, against SoA routing approaches such as shortest path. Simulation results show that the *BP-MR per-flow* approach reveals effective to work not only with UDP but also to work with TCP while retaining most of the good features of the *per-packet* strategy. Further improvements could be expected in the case of increased network redundancy, such as envisaged urban scenarios.

Acknowledgments

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