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Smart Gateway Diversity Strategies for Q/V Feeder Links in SDN-Satellite Networks

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***Abstract*—With the continuous improvements in communication technologies, users are demanding services with even higher and higher performance. High Key Performance Indicators (KPIs) have been set for this purpose in defining the next upcoming generation of mobile communications (5G). New emerging use cases and applications are enriching the already vast plethora of services that users can exploit through the Internet. However, traditional terrestrial networks have some intrinsic limitations that cannot be overcome with technology enhancements. For example, the terrestrial infrastructure will never be able to reach certain areas due to physical constraints, such as oceans, or the lack of a proper economic advantage, such as under-populated rural and remote areas.**

Satellite networks are foreseen to help the terrestrial infrastructure in several ways, especially in boosting enhanced Mobile Broadband (eMBB) services in converged 5G-satellite systems. New frequency bands have to be considered in order to guarantee the high required data rates. However, additional aspects should also be considered in order to deal with some impairments, such as the severe weather impairments that satellites need to tackle at high frequencies (Q/V bands).

This paper proposes a novel smart gateway diversity strategy and validates its design through simulation campaigns, whose preliminary results show important performance gains with respect to other solutions available from the existing state-of-the-art.

I. Introduction

Due to the growth of the traffic volume on the Internet, which will further increase in the near future, traditional terrestrial systems will not be able to satisfy all users' demands all over the world. Employing Satellite Communication (SatCom) networks to support the terrestrial ones and to overcome their limitations is one of the key solutions to increase the offered coverage and the network throughput, both being requirements to match for the 5G ecosystem's growth. Data exchange through satellite links should exploit higher frequency bands compared to the ones used in current SatCom systems, in order to allow them to manage traffic flows while respecting the required 5G Key Performance Indicators (KPIs). Q/V frequency bands (33$\div$75 GHz) seem suitable for this purpose, even if attenuations due to rain and clouds is strong at these frequencies and it can lead to temporary outages in the feeder links. Some impairment mitigation techniques have been developed. An example is Adaptive Coding and Modulation (ACM), which involves the change of the modulation and of the robustness of the code (MODCOD) depending on the current measured attenuation level. Even if the usefulness of ACM has been proven and it is currently employed in different satellite communication protocols such as DVB-S2 [1] and DVB-S2X [2], this technique is not effective to cope with attenuations on the link between gateways and satellites. The main reason is the decrease of spectral efficiency induced by the change of waveform which would affect all the user terminals thus leading to possible network congestions.

The concept of Smart Gateway Diversity was introduced to help overcome this issue. In a SatCom network where a set of gateways are linked together through high-speed terrestrial links, to design the ground segment with certain distances between each couple of gateways helps exploit the spatial decorrelation of rain attenuation. In this way, when a gateway's satellite link suffers from high attenuation and consequent outage, the other gateways support it until the outage ends, obtaining an increase of the network availability and throughput.

In the past years, research studies and projects have been carrying on aimed at investigating this issue.

The Gateway Diversity concept has been initially defined in [3], where the authors consider the single site diversity as a special case of the smart gateway one. After this first study, further works have been performed aimed at properly managing data traffic flows to upload on a satellite moving them from one gateway to another in case of possible outage. Authors in [4] modified the Switch and Stay Combining scheme to achieve transmission diversity through Q/V band feeder links. The investigated approach activates only one gateway at a time depending on the measurements of the attenuation levels due to atmospheric events, decreasing the switching rate between gateways without any performance decay. The multiple gateway transmission diversity case is considered in [5] where the switching model is applied when changing the feeder link of the satellite network to Q/V band. The robust Modified Switch and Stay Combining (MSSC) strategy is employed together with information about the Signal-to-Noise Ratio (SNR) to federate the gateways into switching pairs. The obtained results show better performance with larger cluster, thanks to the higher ratio of both active and redundant gateways. Two different approaches to design the network architecture considering the gateway diversity principle are presented in [6]: "N-active" and "$N+P$" (also formally defined in the patent [7]). In the first case, also called "$N+0$" scheme, all gateways (N) are active and available to forward data at the same time gaining access to the shared satellite channel through frequency or time multiplexing. In the "$N+P$" case, there are two sets of gateways: N active gateways and P redundant gateways. The gateways of the latter set act as backup nodes and become active only when at least one of the initial active gateways is in outage. Gateways' position must be properly set to, on one hand, let them lay within the same satellite feeder beam and, on the other hand, avoid them suffering from the same attenuation event (spatial decorrelation). A deeper performance analysis has been carried out in [8] comparing the N-active with time multiplexed and "$N + P$" gateways schemes. Probabilistic assumptions are considered in [9] for gateway outage in both "$N + 0$" and "$N + P$" schemes, collecting results aimed at assessing the efficiency of outage prevention when a sufficient number of gateways is available. The subsequent step in the performed research on this topic involves studies to test the joint employment of gateway diversity schemes and outage prediction algorithms. The main aim is to evaluate how the obtained performance may further improve if the employed scheme can forecast the satellite link outage in advance. Different forecasting mechanisms to control the switching operation between gateways have been proposed in [10] and [11]. A channel estimation algorithm is applied in [12] and [13] to assist the prediction of possible handover events when an outage is assumed to occur. The adoption of network coding is also considered to handle the packet losses in case of prediction inaccuracies, in order to better protect the system at the cost of additional redundancy. An accurate prediction algorithm based on time adaptive linear regression is proposed in [14]. This algorithm aims to overcome the problem of link outage in Very High Throughput Satellite (VHTS) systems operating in Q/V bands and to establish efficient gateway handover strategies in order to guarantee high system availability. A forecasting algorithm based on machine learning implemented within an SDN architecture framework has been employed and tested in [15]. Several classification algorithms running within an SDN controller exploiting the required information about the controlled network have been assessed.

From the research project viewpoint, QV-LIFT [16] is a research project funded by the European Union in 2016 with the main aim of studying, developing, and testing smart gateways solutions for satellite networks operating in Q/V frequency bands. A description of both hardware and software developments of the considered "N+P"-based gateways system and of the considered gateways switching strategy is reported in [17] and [18].

The satellite scientific community and industry have worked hard in the last decade to explore these concepts and to conduct important experimentation campaigns by dedicating particular attention to the design of the ground segment from a physical layer point of view. However, less importance has been given so far to the higher protocol layers. Consequently, a comprehensive system analysis is missing. In particular, very few scientific works have addressed, at the best of the authors' knowledge, the problem of providing an efficient QoS management framework to VHTS systems. The limited existing literature elaborates mostly on the case of a few interconnected gateways and investigates the overall QoS system performance only partially. To bridge the existing scientific gaps, this paper provides a holistic framework to address QoS management in VHTS systems when sophisticated link outage prediction algorithms have to be combined with efficient re-routing algorithms aimed at minimising network congestion events.

The remainder of this paper is organised as follows. The reference scenario and the system model are provided in Section II. The proposed handover algorithm is illustrated in Section III, where also other candidates solutions taken as benchmark are briefly discussed. Performance results are then provided and described in Sections IV, while the conclusions are drawn in Section V.

II. Aim and Scope

A. Reference Scenario

In this paper, we consider the same reference scenario as in our previous contribution [15], i.e. the star multi-beam multi-gateway satellite network depicted in Figure 1.

Satellite gateways (GWs) are the access nodes to the space segment and are interconnected through a terrestrial infrastructure. Satellite feeder links between a Geostationary (GEO) satellite and the GWs operate in Q/V frequency bands implementing the DVB-S2 technology. A set of Network Control Centers (NCCs), co-located in the GWs, contributes to the network management periodically collecting measured Signal-to-Noise (SNR) values of the feeder links. The NCC/GW Manager is in charge of estimating the evolution of each gateway channel's quality and predicting future outage events exploiting the information received from the NCCs. Current and estimated future network status could affect the dynamic GW selection, i.e. the data routing strategy within the ground segment, in order to better exploit the available network resources.

The Software Defined Networking (SDN) concept [19] helps achieve this task allowing to dynamically set up different routing paths for different traffic flows. A central entity, called SDN controller, canalizes traffic flows through the selected GWs computing and sending proper forwarding rules to SDN-enabled devices (Ss), called SDN switches. These nodes follow the received rules keeping them stored in a table called flow table. When a new flow enters the network, the incoming SDN switch checks if a proper rule is already stored in its flow table. If it succeeds, it proceeds forwarding data, otherwise, it asks for instructions. Information about traffic flows' maximum acceptable delay, minimum required throughput, maximum tolerated loss, as well as GW buffer occupancy and future feeder link outage events, can be considered for rule computation.

B. System model

N gateways ($GW_1, \ldots, GW_N$) are connected to the GEO satellite and to the terrestrial infrastructure through N SDN switches ($S_1, \ldots, S_N$). Each GW includes its local NCC ($NCC_1, \ldots, NCC_N$) in the same physical node. SDN switches are controlled by an SDN Controller by using the standard de-facto protocol OpenFlow (OF) [20]. GWs and NCCs are managed by the NCC/GW Manager through dedicated control protocols. Both SDN controller and NCC/GW manager are included in a central joint entity (Central node) that encases the intelligence of the entire network. The central node is in charge of associating each new incoming traffic flow to the proper GW, predict feeder link outage events exploiting satellite links' SNR measurements, and manage all additional functionalities related to the outage events reaction.

We assume that each traffic flow f generates packets at a mean bit rate $r(f)$. In this way, the Central Node is able to

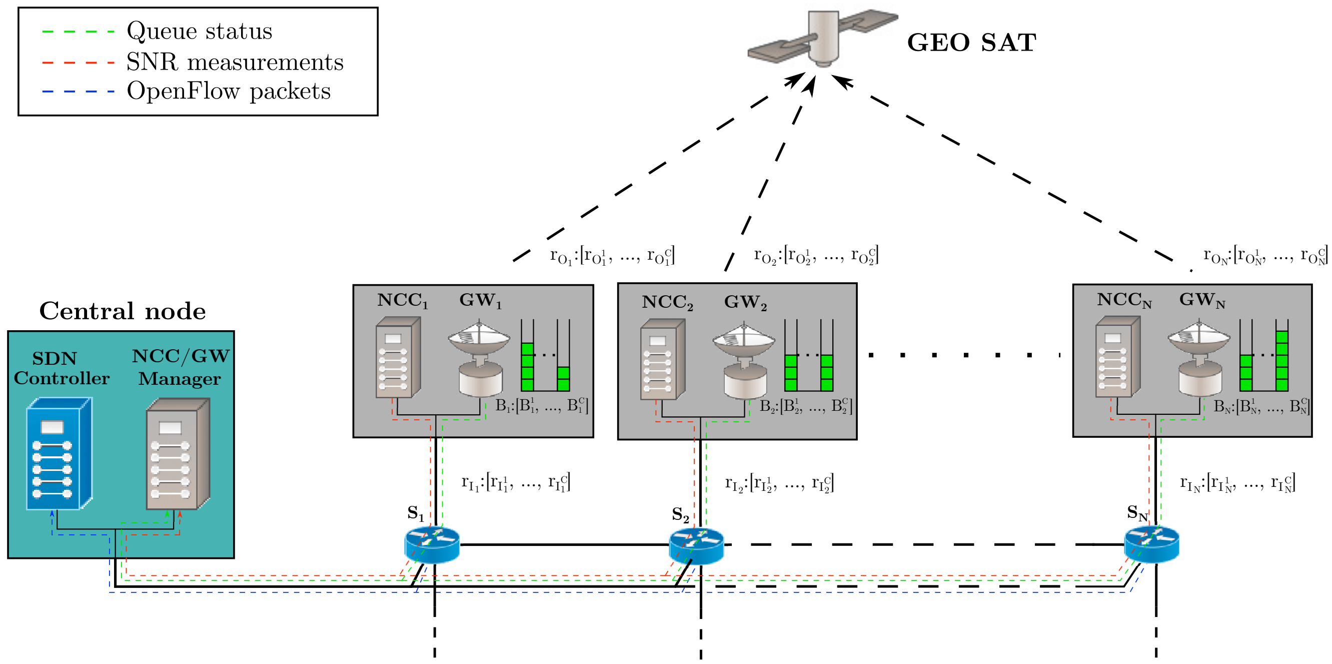

Fig. 1. Smart Gateway Diversity scenario

compute the current mean input data rate r_{I_n} of each gateway GW_n as $r_{I_n} = \sum_{f=0}^{F_n} r(f)$, F_n being the number of flows currently allocated to GW_n. The current achievable output data rate r_{O_n} of each gateway GW_n is affected by the employed Modulation and Coding (MODCOD) and its related spectral efficiency, which is tuned according to the measured SNR. Table 13 in [1] contains all the required information to obtain current r_{O_n} values from measured SNRs for the DVB-S2 standard. B_n denotes the buffer occupancy of GW_n, i.e. the amount of data stored in its buffer waiting to be sent through its satellite link.

We consider C traffic priority classes whose traffic flows generate packets with mean bit rate r^c and require different minimum performance in terms of guaranteed throughput. The mean input rate of GW_n can be re-defined as $r_{I_n} = \sum_{c=1}^{C} r_{I_n}^c = \sum_{c=1}^{C} r^c \cdot F_n^c$, F_n^c being the number of flows of the c-th traffic class associated to the n-th gateway. In the same way, by using the same notation, we can re-define the buffer occupancy of GW_n as $B_n = \sum_{c=1}^{C} B_n^c$. r_{O_n} can be split in C portions $r_{O_n}^c$ employing a proper scheduling policy, e.g. Weighted Round Robin (WRR), in order to reserve a proper portion of the available bandwidth to each class, such that $r_{O_n} = \sum_{c=1}^{C} r_{O_n}^c$.

III. Handover Strategies

A. Proposed strategy

Our proposed handover strategy aims to properly balance the incoming traffic through all the available GWs in order to guarantee the required performance for each traffic flow. In case of outage events, i.e. the satellite channel attenuation is high enough to prevent communications even by using the strongest MODCOD, the affected GW is unable to send packets until the outage period ends, forcing the SDN controller to properly update SDN switches' flow tables and re-route traffic packets, if necessary. The strategy is structured in the following steps:

traffic flow association: For each traffic class, we set a performance constraint in terms of minimum guaranteed throughput per flow r_g^c. When a new traffic flow of the c-th class enters the network, the Central Node starts the *traffic flow association procedure*. Let $\mathcal{GW}$ denote the set of GWs available for the association process, $r_{O_n}^{*c}(p)$ denote the estimation of the output data rate of GW_n related to the c-th traffic class at time p, P the number of considered estimated samples, and α_p a weight assigned to the p-th sample; the Central node associates the new flow to the gateway $GW_{\bar{n}}$ which maximizes the following quantity Λ_n^c, after verifying it can ensure the minimum throughput r_g^c:

$$\bar{n} = \arg\max_{n \in \mathcal{GW}} [\Lambda_n^c];\ \Lambda_n^c = \sum_{p=0}^{P} \alpha_p r_{O_n}^{*c}(p) - r_{I_n}^c \qquad (1)$$
$$\Lambda_n^c \geq r_g^c$$

For simplicity, the current value of $r_{O_n}^c$ will be henceforth referred to $r_{O_n}^{*c}(0)$. Including both the current and P estimated values of $r_{O_n}^c$ allows considering the achievable output rate trend in an arbitrarily long future. The set of values $\alpha_p \in [0,1]$, $p = 0, \ldots, P$, $\sum_{p=0}^{P} \alpha_p = 1$ allows arbitrarily setting the contribution of each sample.

traffic flow re-allocation: If a satellite link's SNR $SNR_{n'}$, and $r_{O_{n'}}$ consequently, starts decreasing, $r_{I_{n'}}$ can become higher than $r_{O_{n'}}$, and $B_{n'}$ starts increasing (congestion situation). A re-allocation of one or more traffic flows to one or more other GWs would relieve the congestion and avoid packet losses due to buffer overflow. Besides, a decision about traffic flow re-allocation can take place exploiting $r_{O_n}^{*c}$ knowledge. We exploit SNR prediction to make congestion prediction and react in advance. The Central Node periodically updates all Λ_n^c values and initializes the *traffic flow re-allocation procedure* in case of predicted congestion, re-allocating the minimum number of traffic flows. First, it selects the traffic class of the GW that will give rise to the congestion, i.e. the c'-th class of the n'-th GW such that $\Lambda_{n'}^{c'} < 0$. Then, it re-selects another GW among the non congested ones as in Eq. (1). The first re-allocated traffic flows are the more recent ones, in order to try minimizing the number of times the re-allocation process is performed and, as a consequence, the number of re-allocated flows. In this way, the SDN switches' flow tables will be updated in order to forward the new incoming packets of the re-allocated flows to the new selected GWs, lowering $r_{I_{n'}}$ until $\Lambda^{c'}_{n'}$ becomes positive again.

outage: When the prediction algorithm identifies an upcoming outage event in t_d, the SDN controller has to properly react in order, on the one hand, to allow the affected GW $GW_{\mathcal{N}}$ to empty its buffer before the outage begins and, on the other hand, to avoid waste of available satellite bandwidth, i.e. allow $GW_{\mathcal{N}}$ to upload packets to the satellite for as long as possible. The Central node starts the *outage procedure*. First, it avoids that new traffic flows will be associated to $GW_{\mathcal{N}}$ removing it from $\mathcal{GW}$. Afterward, it periodically estimates the amount of data that $GW_{\mathcal{N}}$ can send before the predicted outage begins as:

$$\lambda_{\mathcal{N}} = \sum_{c=1}^{C} \lambda^c_{\mathcal{N}} = \sum_{c=1}^{C} \int_0^{t_d} r^{*\,c}_{O\mathcal{N}}(t)\, dt \tag{2}$$

If $\lambda_{\mathcal{N}} > B_{\mathcal{N}}$, the SDN switches keep forwarding packets to $GW_{\mathcal{N}}$. When $\lambda_{\mathcal{N}}$ becomes lower than or equal to $B_{\mathcal{N}}$, the re-allocation process starts re-allocating all traffic flows from $GW_{\mathcal{N}}$ to one or more other GWs. If $\lambda_{\mathcal{N}}$ is already greater than $B_{\mathcal{N}}$ when the outage is predicted, $GW_{\mathcal{N}}$ will not be able to send all the packets stored in its buffer before the outage begins. To prevent a long waiting time until outage end, a *packet re-routing procedure* moves packets from $GW_{\mathcal{N}}$ to one or more other GWs through the terrestrial segment. $\sigma^c_{\mathcal{N}} = \lambda^c_{\mathcal{N}} - B^c_{\mathcal{N}}$, $\sigma^c_{\mathcal{N}} > 0$, $\forall c = 0, \ldots, C$ denotes the amount of data of the c-th traffic class that needs to be re-routed. The GW which will receive the re-routed packets is selected for each traffic class as in Eq. (1). An additional control is also performed on the selected GWs' buffer occupancy to avoid packet losses due to buffer overflow. When the prediction algorithm output is again a 'no outage' decision, i.e. the outage is ending, $GW_{\mathcal{N}}$ is considered available again and re-inserted in $\mathcal{GW}$ for the association process before the outage end. In this way, $GW_{\mathcal{N}}$'s buffer will not be empty when its satellite link will be active again, avoiding waste of bandwidth right after the end of outage events.

B. Static strategy

When an outage event is predicted for the GW $GW_{\mathcal{N}}$, the Central Node always re-allocates the traffic flows from $GW_{\mathcal{N}}$ to another gateway statically selected. These static bonds between couples of GWs can be set by using different criteria, such as the geographical distance between GWs, are bidirectional, and are fixed over time. No information about the current or predicted status of the network is needed. GW selection for packet re-routing after the outage beginning is performed in the same way. This strategy offers a simpler outage event management even if the static GW selection can have several drawbacks, such as traffic flow performance degradations and congestion situations on the selected GWs.

C. Network Coding-based strategy

Let P^c_n denote the number of class c's packets stored in GW_n's buffer, every time the Central node predicts an outage event in a GW $GW_{\mathcal{N}}$, C sets of m^c network coding packets each are generated from the C sets of k^c original data packets, where $k^c = P^c_{\mathcal{N}}$, $c = 0, \ldots, C$ and the m^c values are dynamically set. In detail, the Central node periodically estimates the amount of data $\lambda_{\mathcal{N}}$ that $GW_{\mathcal{N}}$ can send before the predicted outage begins as in Eq. (2), and, consequently, the $\lambda^c_{\mathcal{N}}$ values. If $\lambda_{\mathcal{N}} > B_{\mathcal{N}}$, the SDN switches keep forwarding packets to $GW_{\mathcal{N}}$, and when $\lambda_{\mathcal{N}} \leq B_{\mathcal{N}}$, the outage procedure is triggered. The amounts of generated network coding packets are set as $m^c = \mathcal{P}(B^c_{\mathcal{N}} - \lambda^c_{\mathcal{N}})$, where the operation $\mathcal{P}(x)$ indicates the lowest amount of stored packets whose overall size is greater than or equal to x. In this way, assuming reliable the estimation, the first $\mathcal{P}(\lambda^c_{\mathcal{N}})$ packets stored in $GW_{\mathcal{N}}$ will be sent by $GW_{\mathcal{N}}$, while the m^c generated packets will be forwarded through another GW selected as in Eq. (1). When the outage starts, the packets still stored in $GW_{\mathcal{N}}$'s buffer are dropped. The packets reception is considered successful if at least k^c packets are correctly received, otherwise, the whole block of received packets cannot be decoded and they are considered lost. This strategy allows high robustness against packet loss due to outage at the cost of an increase of the traffic volume; this is the reason why the m^c values should be set considering the trade-off between increased traffic volume and loss protection.

D. Drop strategy

When an outage event is predicted for the GW $GW_{\mathcal{N}}$, the Central Node re-allocates the traffic flows from $GW_{\mathcal{N}}$ to another gateway selected as in Eq. (1). If $GW_{\mathcal{N}}$'s buffer is not empty when the outage event starts, all the stored packets are dropped. There is not packet re-routing among GWs. This strategy aims at reducing the traffic volume which "horizontally" traverses the ground segment.

IV. Performance Evaluation

A. Simulation Setup

To simulate the scenario depicted in Figure 1, we use a discrete event simulator written in Python and based on the process-based discrete-event simulation library Simpy.

The design parameters of the considered scenario are summarized in Table I.

TABLE I. Simulated scenario design parameters

Number of GWs N	5
GW buffer size	10 Gb
Number priority classes C	3
Flow guaranteed throughput r^c_g	[8 4 2] $Mbps$
Packet inter-generation time	[25 50 100] ms
Packet size	200 kb
Flow duration	1 200 s
Number predicted samples P	10
Size of the observation windows T	10
Predicted sample weights α_p	$\dfrac{1}{P+1} = \dfrac{1}{11}$
SNR outage threshold (SOT)	$-2.35\ dB$
Simulation duration	100 $days$

The simulated traffic flows are Constant-Bit-Rate (CBR) flows whose parameters are reported in Table I. Traffic flows' start times are randomly generated with a uniform distribution for the whole simulation duration. Each flow's priority class is also randomly generated with a uniform distribution.

Since we are interested in assessing our proposed handover strategy which acts on the feeder link, simulated traffic is generated from the ground segment and forwarded up to the

GEO satellite (user link is not included in the simulation environment).

We decided to homogeneously set the α_p values for all the considered estimated samples and the current one, i.e. both current and estimated values contribute to the GW selection with the same weight.

The set outage threshold on the measured SNR is the one of the strongest MODCOD of DVB-S2 (QPSK 1/4), as reported in [1], Table 13.

Since rain attenuation is a time varying process, we modeled it as a first order Gauss Markov process of the Ornestein-Uhlenbeck type, generating N different and independent attenuation traces in dB as detailed in [21]. We obtained N SNR traces from these attenuation traces through a proper link budget and, in run time, the simulator computes the current GW output rate values from the related SNR samples considering the spectral efficiency of the selected DVB-S2 MODCOD reported in [1], Table 13.

B. Results

In order to better highlight the network behaviour in case of outage events, the shown results regard a small portion of the overall simulation results: the one collected in preparation, during, and after one outage event. In this considered time window, one of the GWs (G_0) is approaching an outage event which takes place and lasts about 100 seconds. Figure 2 shows the SNR trends of all the simulated GWs in the considered time window.

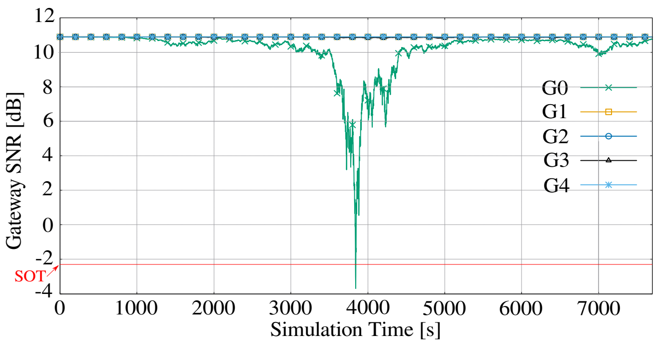

Fig. 2. Gateway SNR traces

Looking at the SNR trend of G_0, it starts fluctuating while approaching the outage event and then decreasing until it reaches the outage threshold. To mitigate the effect of fluctuations, we employ a hysteresis mechanism that prevents the frequent transitions between normal and outage states and vice versa, "merging" together smaller outage intervals in a single one.

The obtained performance has been assessed considering the Normalized Throughput (NT) performance metric. The performance obtained by using our proposed strategy has been compared with the one obtained by using the other three strategies described in Section III considered as a benchmark.

Figure 3 shows the NT of the GW uplink channels.

When all the GWs have the same SNR values, the Central node homogeneously distributes the new incoming traffic flows to the all GW set, as testified by the GW NT values. When G_0's channel quality starts decreasing, we can see fluctuations of G_0's NT due to the formed unbalanced situation among GWs which is automatically recovered by the traffic association process. However, when G_0 approaches the outage, its channel quality rapidly decreases, leading to congestion due to the severe unbalance between overall input and output rates. Our solution is the only one among those considered which can sense this situation and trigger the traffic flow re-allocation procedure, avoiding packet losses and keeping guaranteeing each traffic flow's required throughput. Looking at G_0's NT right before the outage beginning, it never reaches the maximum value with our solution (Figure 3a), unlike with the other solutions, avoiding an increase of the GW buffer occupancy and, consequently, possible losses due to buffer overflow.

Figure 4 shows the NT of a traffic flow affected by congestion, i.e. the ratio between the actual amount of data sent to the satellite and the amount of data that would have been sent to the satellite in the same time interval to satisfy the defined QoS in terms of traffic flow throughput. Looking at Figure 4a, the employment of our solution guarantees the required throughput of the analysed traffic flow for all its duration, while it cannot be fulfilled by the other strategies.

When the outage starts, G_0 is no longer able to send packets and its NT becomes zero, while the other GW's NTs have different trends depending on the tested strategy. This leads also to different performance from the traffic flow viewpoint, as highlighted by the NT of a traffic flow affected by outage, i.e. associated to G_0 when the outage is predicted, shown in Figure 5.

With our proposed strategy, the Central Node starts re-allocating traffic flows from when it sensed the congestion, and possible packets still stored in G_0 buffer when the outage starts are homogeneously distributed to all the other GWs. Also in this case, the required throughput of the analysed traffic flow is fulfilled (Figure 5a). No packet loss has been detected during the simulation.

With the static solution (Figure 3b), the traffic flow re-allocation takes place only in the time interval between the outage prediction and the outage beginning, and all packets stored in G_0's buffer which cannot directly be uploaded to the satellite are statically forwarded to another GW (G_1), independently of its buffer occupancy and channel quality. This leads to a rapid increase of G_1's NT and packet losses due to buffer overflow. The analysed traffic flow's NT (Figure 5b) demonstrates this behaviour, where the low values are due to the pre-outage congestion and the peak due to the re-routing of the block of packets still stored in G_0's buffer when the outage starts. An overall PLR of 0.06% has been measured.

With the network coding-based strategy (Figure 3c), the traffic flow re-allocation takes place only in the time interval between the outage prediction and the outage beginning, all packets stored in G_0's buffer are not re-routed, and the generated network coding packets per traffic class are sent to other gateways. In this test, the three packet blocks, one for each defined priority class, are forwarded to three different GWs (G_1, G_2, and G_3). This lowers the congestion effect spreading the packets through more selected gateways than the single one of the static case, offering better performance as can be seen looking at the higher peak in Figure 5c and lower overall PLR of 0.03%. However, the network coding-based strategy can relieve but not solve the problem already noticed with the static solution.

With the drop strategy (Figure 3d), the traffic flow re-

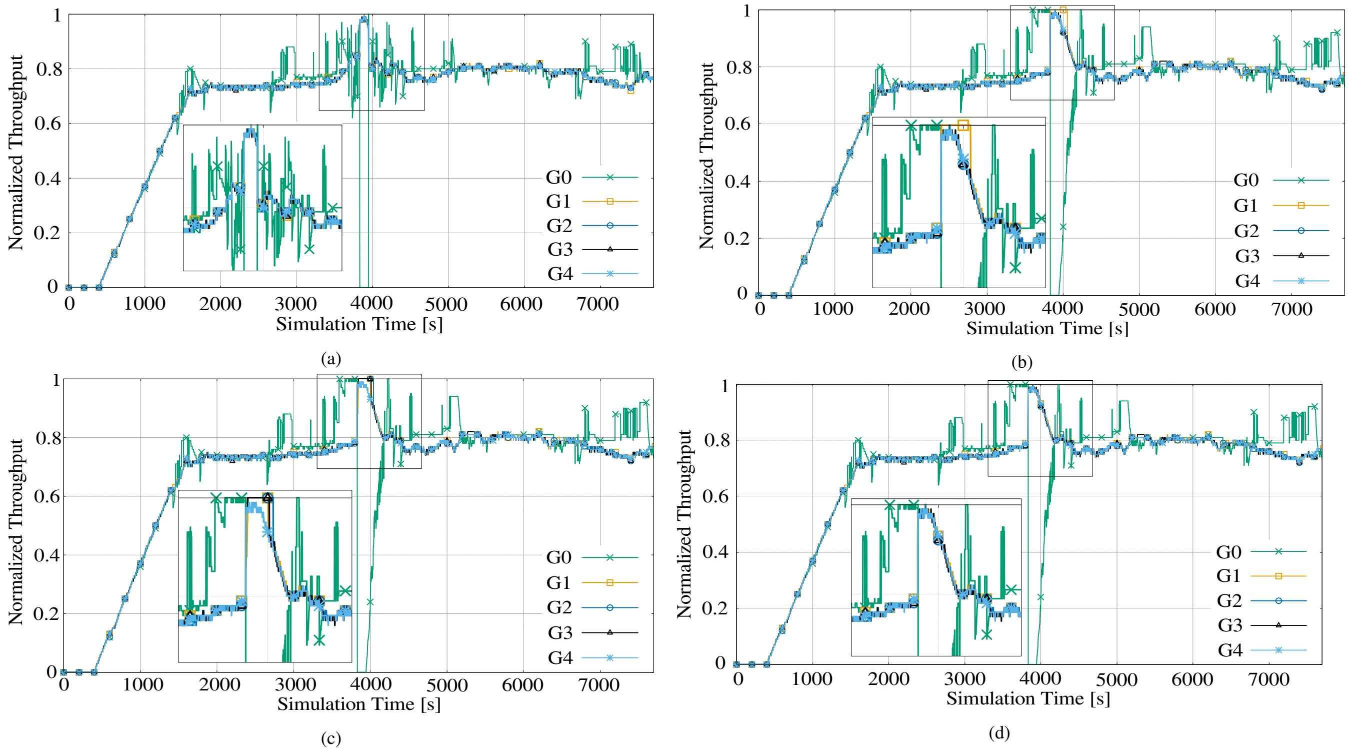

Fig. 3. GW uplink channels' NT: our (a), static (b), network-coding based (c), and drop (d) solutions

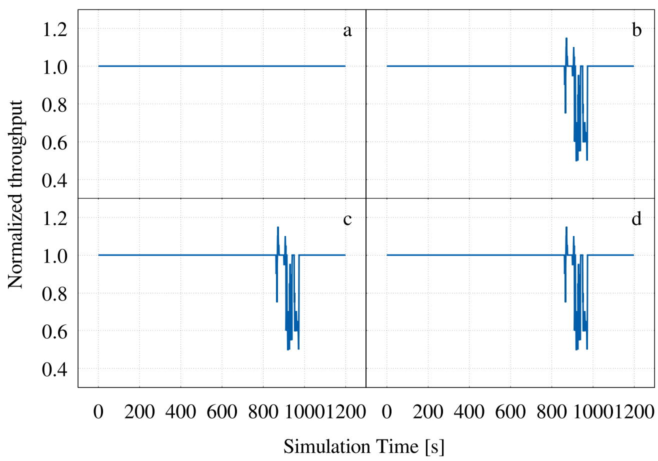

Fig. 4. NT of a traffic flow affected by gateway congestion: our (a), static (b), network-coding based (c), and drop (d) solutions

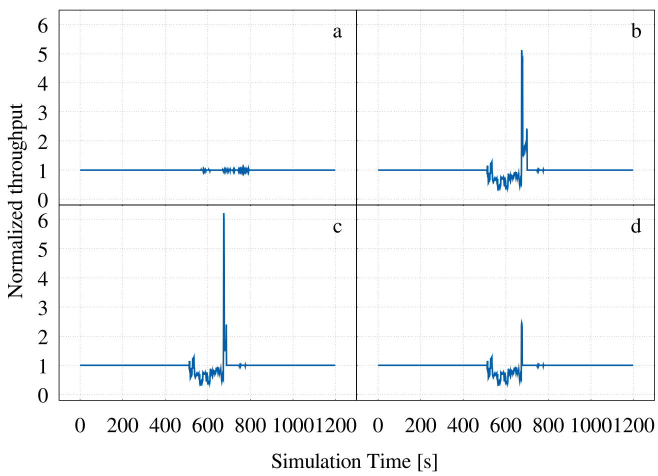

Fig. 5. NT of a traffic flow affected by gateway outage: our (a), static (b), network-coding based (c), and drop (d) solutions

allocation takes place only in the time interval between the outage prediction and the outage beginning, all packets stored in G_0's buffer are not re-routed and if they are not sent before the outage begin they are dropped. This affects the GW's NT which homogeneously increases to compensate G_0 outage and leads to a severe performance worsening of the traffic flow affected by outage, as can be seen looking at the analysed traffic flow's NT in Figure 5d and by the obtained overall PLR of 0.09%.

When the outage ends and G_0's link returns active, G_0's NT with our solution almost instantly reaches the other GW's NTs, avoiding waste of G_0's link bandwidth. On the contrary, G_0 and the others' NT with the other solutions gradually increases and decrease, respectively, until reaching the balanced pre-outage situation, slowly relieving the additional load on the other GWs.

Another set of tests has been performed simulating Variable-Bit-Rate (VBR) traffic flows, whose behaviour is more similar to real traffic flows than the CBR ones. In detail, we simulated burst traffic flows with on-off periods of equal duration (duty cycle 50%) where no packets are generated in the off periods and packets are generated in the on periods at twice the data rate reported in Table I.

The obtained performance in terms of GW uplink channels' NT is shown in Figure 6.

The NT trends shown in Figure 6 reflect the fluctuating trend of the number of generated packets over time and shows the wider range of values of $G0$'s NT, which in some time instants reaches the maximum value. However, the additional information regarding the obtained performance and the control overhead of our proposed strategy shown in Table II confirms its correct behaviour and its robustness even in case of VBR traffic flows.

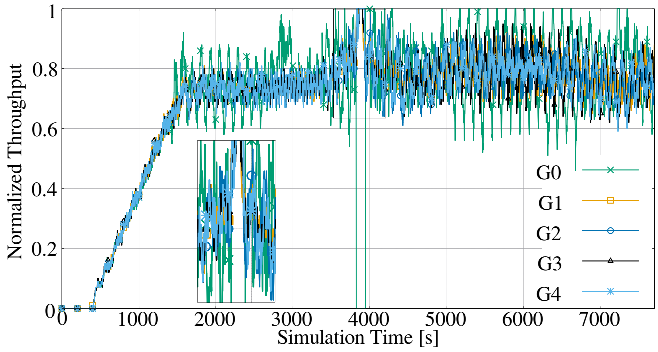

Fig. 6. GW uplink channels' NT with VBR traffic flows

TABLE II. Additional information about the obtained performance and overhead with VBR traffic flows

Mean network NT	0.675	
Mean *G*0 NT	0.674	
Number re-allocated traffic flows (predicted congestion)	351	0.004%
Number re-allocated traffic flows (predicted outage)	195	0.002%
Number lost packets (buffer overflow)	0	0%
Number re-routed packets (outage)	0	0%

V. Conclusions

Increasing the available bandwidth and the achievable data rates is of primary importance to allow the expected users' Quality of Experience (QoE) in the future 5G network. The employment of Satellite Communication networks to support the terrestrial infrastructure is under study and design within the 5G framework to help achieve the defined 5G KPIs. However, there are still open challenges to solve to allow a complete integration between terrestrial and satellite networks. One of them is related to the problem of traffic routing management in Very High Throughput Satellite networks, i.e. operating at higher frequency bands such as Q/V bands. At these frequencies, additional attenuation factors hinder the communications between the satellites and the ground leading to temporary outage events. Proper handover strategies are required to distribute the traffic flow throughout the available gateways and to re-allocate traffic flows in case of gateway link outage.

This paper proposes a handover solution that exploits the available information about the current network status (periodically measured SNR values of satellite links and GW buffer occupancies) to move traffic flows among gateways in case of congestion or outage events. A prediction algorithm is also employed to predict outage events and allow the network to react in advance in order to maximize the available bandwidth exploitation, while minimizing, at the same time, the satellite bandwidth waste.

A performance evaluation has been conducted through a simulation tool comparing our proposed strategies with others in the literature in terms of achieved normalized throughput with different traffic flow configurations. The obtained results assess the performance improvement of the proposed solution and its robustness in different network conditions.

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