# Satellite - 5G Integration: A Network Perspective

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**ABSTRACT**

**Future 5G mobile communication systems are expected to integrate different radio access technologies including the satellite component. Within the 5G framework, the terrestrial services can be augmented with the development of High Throughput Satellite (HTS) systems and new mega constellations meeting 5G requirements, such as high bandwidth, low latency, increased coverage, including rural areas, air, and seas. This paper provides an overview of the current 5G initiatives and projects followed by a proposed architecture for 5G satellite networks where the SDN/NFV approach facilitates the integration with the 5G terrestrial system. In addition, a novel technique based on network coding is analyzed for the joint exploitation of multiple paths in such integrated satellite-terrestrial system. For TCP-based applications, an analytical model is presented to achieve an optimal traffic split between terrestrial and satellite paths and optimal redundancy levels.**

## INTRODUCTION

The vision of 5G is driven by the prediction that data traffic requirements will increase by up to 1000 times by 2020. However, the available spectrum will not be sufficient to satisfy this huge demand. There will be the need to use much smaller cells where resources can be adapted dynamically in space and time [1]. Moreover, techniques like Multiple-Input-Multiple-Output (MIMO) antennas, high-frequency reuse, and precoding will be adopted to enhance the capacity. Moreover, 5G systems will need to achieve important Key Performance Indicators (KPIs), such as low latency, high-level of security, massive device connectivity, and consistent Quality of Service (QoS) provisioning [2]. For instance, 5G is expected to provide user bit-rates up to 10 Gbps and to have Round-Trip Times (RTTs) as small as 1 – 10 ms for some application scenarios.

Recent studies estimate that about 4 billion people of the world's population still lack Internet access. The cost of a pure terrestrial coverage will quickly become unbearable with increasing capacity needs for rural, remote, and even urban areas. Therefore, satellite communications will play a significant role in 5G as a complementary solution for ubiquitous coverage, broadcast/multicast provision, and emergency/disaster recovery [3]. Satellites will have unique opportunities for providing 5G services in rural areas. Moreover, satellites will also support machine-type communications, paving the way to new applications, ranging from smart agriculture, environmental protection, transportation, animal tracking, etc.

By 2020-2025 there will be more than 100 High Throughput Satellite (HTS) systems using Geostationary (GEO) orbits but also mega-constellations of Low Earth Orbit (LEO) satellites, delivering Terabit per second (Tbps) of capacity across the world. It is expected that these evolved satellite systems will provide Radio Access Networks (RANs), called Satellite RANs, that will be integrated into the 5G system together with other wireless technologies, as cellular systems, WiFi, etc. Seamless handover between heterogeneous wireless access technologies will be a native feature of 5G, as well as the simultaneous use of different radio access technologies to increase reliability, availability, and capacity.

After this introduction, this paper provides a brief review of the state-of-the-art of satellite systems and architectures for the future integration in 5G. Then, a possible application of Network Coding (NC) is proposed exploiting the multiple paths allowed by the integration of satellite and terrestrial systems.

## CURRENT ACTIVITIES ON SATELLITE 5G

Today, there is a growing interest in the integration of a satellite component into the 5G ecosystem. The European Space Agency (ESA) has recently launched the 'Satellite for 5G' initiative (ARTES framework) encompassing development projects, service trials, and testbeds for the achievement of the satellite 5G component. Moreover, the EU NetWorld 2020 European Technology Platform, coordinating the EU R&D efforts towards 5G systems, has developed white papers where the satellite is just a 5G RAN. The EU-funded 5G Public-Private Partnership (5GPPP) is another important initiative for the implementation of future 5G systems, where the satellite is a part of the big picture [4].

The 3rd Generation Partnership Project (3GPP) has recently completed a normative specification on "Service requirements for the 5G system" [5] considering together fixed, mobile, wireless, and satellite access technologies. The first 3GPP specification of 5G systems including multi-RAN support is provided by Release 15 (**Phase 1**). This effort will be continued in Release 16 (**Phase 2**) starting by the end of 2018. The China Communications Standards Association (CCSA) has already partnered with 3GPP working on a global 5G standard. ITU-R Working Group 4B is actively involved in the definition of 5G integrated satellite-terrestrial systems within the framework of International Mobile Telecommunications – 2020 (IMT-2020). IEEE has recently set up the "Future Directions Initiative" (including a 5G satellite working group) to define a technology roadmap towards 5G systems and beyond. The 5G India 2020 Forum was constituted in

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September 2017 to prepare a roadmap to adopt the newer technology by 2020. The Telecoms Regulatory Authority of India (TRAI) has already started looking at the spectrum conflicts for 5G satellite services.

On the research side, the EU H2020 Shared Access Terrestrial-Satellite Backhaul Network enabled by Smart Antennas (SANSA) project [6] has envisaged a seamless integration of the satellite segment to boost the performance of mobile wireless networks. Moreover, the EU H2020 Virtualized hybrid satellite-Terrestrial systems for resilient and flexible future networks (VITAL) project [7] proposed novel ways of using Network Functions Virtualization (NFV) and Software-Defined Networking (SDN) for federated satellite-terrestrial networks. The ESA-funded CloudSat project also addressed key issues for the inclusion of a satellite component into future federated 5G virtualized networks. Similarly, the EU H2020 Sat5G project is also looking at implementing 5G SDN and NFV in satellite networks. Finally, the recently-started ESA-funded SATis5 project aims to build a comprehensive 5G testbed to demonstrate the integration of satellite and terrestrial systems.

### *Satellite 5G Scenarios and Use Cases*

ITU-R M 2083 Recommendation classifies three different 5G scenarios, as **Enhanced Mobile BroadBand (eMBB)**, **massive Machine-Type Communications (mMTC)**, and **Ultra-Reliable Low Latency Communications (URLLC)**. These service categories (as well as others) are also considered by 3GPP [8]. In the 5G satellite context, we consider that eMBB and mMTC are common scenarios as shown in Fig. 1, where the satellite backhaul case is also envisaged to interconnect separate parts of the same 5G network [9]. On the other hand, satellite systems can support URLLC-like services that require high reliability and high availability but that do not need extremely low latency because of the large propagation delays.

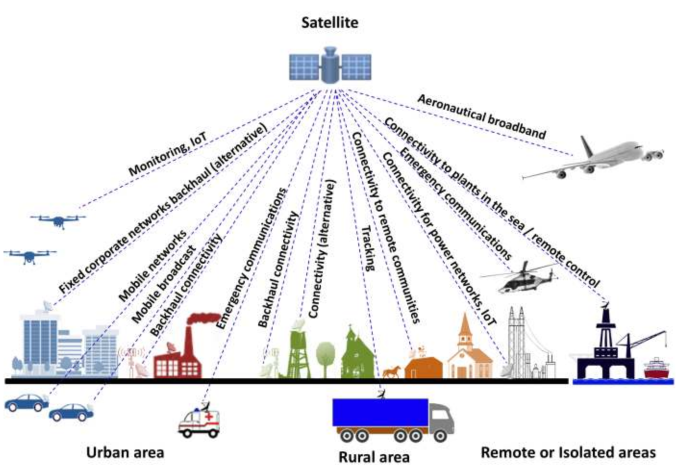


**Fig. 1**: Satellite 5G use cases.

In most eMBB service scenarios, user data rates and spectrum efficiency have high importance. In mMTC service scenarios, the challenge is the expected tremendous number of small devices that occasionally transmit their packets to the satellite; therefore, there is the need of a local data collector that is responsible for delivering these data possibly via LEO satellites [9]. This paper is concerned with the eMBB scenario [8], encompassing users in underserved areas, disaster relief services, emergency communications, media and information for passengers onboard trains, vessels, and planes.

### *HTS GEO Systems*

Looking towards the future to 2020/5 there will be a trend to larger and more powerful GEO satellites. **ViaSat-2** is a Ka-band GEO satellite system providing more than 300 Gbps of total network capacity. ViaSat-2 adopts a dynamic system architecture for auto shifting the traffic among more than 40 Gateways (GWs). **Viasat-3** (expected in 2019) is an ultra-high capacity system comprising three Viasat-3 satellites with more than 100 GWs. The Viasat-3 platform will deliver more than 100 Mbps residential Internet service, enabling 4K ultra-high definition video streaming, and provide up to 1 Gbps for maritime use.

The **Inmarsat's Global Xpress (GX)** network comprises 4 Inmarsat-5 Ka-band satellites, where each Inmarsat-5 satellite will carry a payload of 89 small Ka-band beams. Each satellite will carry 6 fully steerable beams that can point traffic hotspots. GX will deliver download speeds more than 60 Mbps with a latency of around 600 ms. The network has 6 GX satellite access stations acting as GWs. This system supports handovers between GWs to remove the impact of rain fade on feeder links. Moreover, the **Intelsat's Epic$^{NG}$ platform** comprising of 3 satellites envisages delivering high throughput on a global scale.

Other examples of multi-spot beam HTS systems are Eutelsat **KA-SAT**, **SES satellites (**SES-12, SES-14, and SES-15), and Hughes **EchoStar XIX**.

### *New Mega Constellations*

The new mega satellite constellations encompass many satellites and several terrestrial GWs interconnected together by a terrestrial network. In some cases, intersatellite links are available for a fast routing in the sky. Some examples are detailed below.

The **'Other three Billion' (O3B)** satellite delivers Ka-band broadband trunking connectivity (particularly for Africa and Latin America), using up to 20 satellites (by 2021) in a single Medium Earth Orbit (MEO) equatorial ring at an altitude of 8,062 km. O3b does not use intersatellite links but 9 GWs. O3b allows a one-way latency of 179 ms for voice and 140 ms for data services. O3b supports user data rates over 500 Mbps for maritime applications.

**LeoSat** foresees a constellation of 78-108 high-throughput Ka-band satellites (by 2022) in LEO polar orbits at an altitude of approximately 1,400 km. Each satellite in the constellation supports 10 Ka-band steerable antennas, each providing up to 1.6 Gbps; two high-performance steerable antennas, each supporting up to 5.2 Gbps; 4 optical inter-satellite links. One user terminal can exploit up to 500 MHz of bandwidth for both uplink and downlink.

The **OneWeb** system consists of 720 LEO satellites using Ka (20/30 GHz) and Ku (11/14 GHz) frequency bands in near-polar circular orbits at an altitude of 1,200 km. OneWeb will provide the users with high speed (up to 50 Mbps) and low latency (less than 50 ms). It is expected to have approximately 50 or more GWs.

The **SpaceX Starlink** satellite system consists of two sub-constellations. A first LEO constellation comprises 4,425 satellites (by 2024) operating in Ku and Ka bands at around 1,110 km of altitude providing a wide range of broadband communication services to residential, commercial, institutional, governmental and professional users worldwide. A second LEO constellation will be used by SpaceX, having 7,518 V-band satellites at around 340 km of altitude.

Finally, other constellations are under consideration by Boeing - 2,956 satellites at an altitude of 1,200 m by 2022; Samsung - 4,600 satellites at an altitude of about 1,400 m by 2028; Telesat - 117 satellites at altitudes of 1,000 m and 1,200 m by 2021.

### *New Frequency Bands Q/V/W*

The new bandwidths available for 5G satellites are Ka band (28 GHz), Q/V band (37-53 GHz), and in sub-6 GHz band. The feeder link from the terrestrial GW to the satellite can also use optical bands. The U.S. Federal Communications Commission (FCC) has adopted new rules for wireless broadband operations in frequencies above 24 GHz for next-generation wireless services. After 2019, it will be possible to exploit mm waves above 24 GHz, following WRC-19. These high-frequency bands are more sensitive to meteorological effects and therefore suitable physical (PHY) layer schemes and GW redundancy must be provided to avoid system outage events. The W-band (75-110 GHz) has a great potential for satellite communications: adding the W-band to Q-/V-band feeder links will allow almost halving the number of GWs, thus reducing the high deployment and operational costs.

## 5G SATELLITE SYSTEM ARCHITECTURE

5G systems are based on the concept of virtualization with the separation of *user plane* (part of the network that actually carries the traffic) and *control plane* (part of the network that determines the traffic route and provides the management), and possibly, the re-definition of the boundaries between radio access network and core network by means of the Could-RAN (C-RAN) approach [10]. The virtualization allows reproducing network functions as logical entities such as logical switches, logical routers, logical GWs, assembled in any topology. The network can be treated as a *resource* to be assigned dynamically. This approach is very important to differentiate various classes of data traffic, e.g., sensors, city cameras, self-driving cars, real-time communications, and assign resources based on business priorities and SLAs. *Network slicing* allows a network operator to define dedicated virtual networks sharing the same physical infrastructure (i.e., RAN). Each slice entails an independent set of logical network functions optimized to provide the resources for the specific service and traffic that will use the slice. Several network functions can be virtualized, such as Authentication Server Function (AUSF), Access and Mobility Management Function (AMF), Session Management Function (SMF), etc.

The software orchestration mechanism, i.e., SDN, entails a programmable network infrastructure. The network intelligence resides in software-based SDN controllers, and network equipments can be configured externally through vendor-independent management software. SDN allows both the centralization of some management functions and the dynamic optimization of the system. The SDN architecture is organized into three different layers:

- **Application Layer** hosting the applications and communicating with the SDN-enabled controller(s) via a standardized Application Programming Interface (API).
- **Control Layer** for the definition of several virtualized networks (network slices) and their orchestration. This layer encompasses SDN controllers, NFV manager, and service orchestrator(s) to control and manage both physical and virtualized network functions.
- **Physical network infrastructure layer** including all the physical nodes that are virtualization-capable, such as GWs, routers, base stations (called gNBs in 5G systems), and the transport network.

In an SDN/NFV-based satellite system, the physical GW hosts the non-virtualized part of the satellite GW and is directly connected to the antennas for satellite signal transmission/reception. Logical services like Performance Enhancing Proxy (PEP), Virtual Private Networks (VPN), offloading, Network Coding (NC), and routing may be customized to the needs of its operator and run as virtualized network functions on top of the same physical infrastructure. The SDN controller should integrate the typical functions of the satellite operation and control center, such as routing policy definition, security, resource allocation, and mobility management. Control decisions are sent to the data plane that is responsible for translating them into management actions. Finally, the data plane forwards the packets using flow table match-action protocol. The next two sub-Sections present the Satellite RAN architecture and a possible structure of the integrated 5G system.

### *Satellite RAN Infrastructure for 5G*

Figure 2 shows a proposed all-IP Satellite RAN architecture for the eMBB scenario where the GW has a key role: on one side, the GW is connected with the 5G Next-Generation Core (NGC) network providing the interface to the Internet and other terrestrial RANs; on the other hand, the GW is also an earth station with a radio feeder link connecting with the satellite [11]. Two alternative approaches are possible in the eMBB scenario: the 5G base station (gNB) is co-located with the GW if the satellite is bent-pipe or is on the satellite for an onboard processing satellite. According to the C-RAN concepts, the gNBs processing functions could also be virtualized and carried out remotely in the cloud.

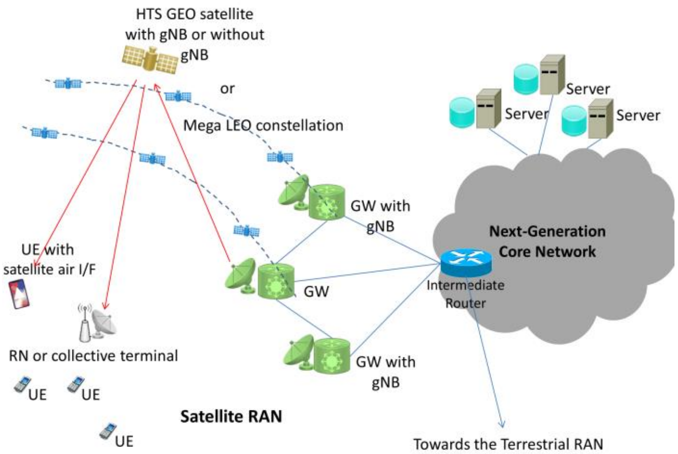


**Fig. 2**: Satellite RAN architecture (eMBB scenario).

In the Satellite RAN, there should be multiple GWs with a certain degree of redundancy to cover situations where the feeder link experiences outage because of bad weather conditions. The GWs should be interconnected using a terrestrial infrastructure to facilitate GW handover functions. The satellite segment should be composed of few GEO HTSs or a constellation of LEO/MEO satellites.

The satellite terminal can be either a small aperture terminal or a handheld User Equipment (UE) with a small antenna. In an integrated scenario, the UE must be capable of exploiting satellite and terrestrial links simultaneously. The satellite terminal could also be a collective terminal interconnected with multiple user devices or a Relay Node (RN) connected with UEs via a radio link. In group mobility scenarios, such as trains and buses, RNs are useful to reduce the handover signaling load on the satellite RAN.

Fig. 2 also highlights an *intermediate router* (i.e., a PEP in the source-to-destination path) that can distribute the traffic towards both satellite and terrestrial RANs of the 5G system. In this paper, we will consider that this special router performs NC to protect from packet losses before splitting the encoded traffic towards both satellite and terrestrial RANs to reach the same user terminal. In turn, the user terminal should be able to perform the joint decoding of the two paths.

### *Integration of Terrestrial and Satellite RANs in a 5G System*

To achieve the prospected integration of the Satellite RAN into the future 5G system there is the need to achieve on the one hand the abstraction of the satellite network and on the other hand to federate satellite and terrestrial RANs assuming they belong to different domains. Although different RANs may likely utilize different physical layer settings and signal processing approaches, higher protocol layers and related network functions should be very similar in an integrated system to reduce infrastructure and device complexity. This approach is made possible by virtualization.

Figure 3 describes an integrated 5G architecture considering a centralized scheme. This architecture derives from similar schemes appeared in VITAL EU H2020 project, 5G-PPP, the CloudSat ESA project, and the ETSI Industry Specification Group on NFV.

The **physical infrastructure** level (user plane) consists of a Satellite RAN (as described in Fig. 2), a Terrestrial RAN with its physical components, and the interconnecting transport network.

The **logical level** (network virtualization) consists of logical nodes such as logical GWs for the Satellite RAN and logical gNBs for the Terrestrial RAN component. At this level, a controller supports the control plane of physical nodes and an NVF manager coordinates the virtualized functions. On top of the logical level, we have a Multi-Domain Orchestrator (MdO) that keeps updated information about the underlying satellite and terrestrial domains and hosts the logic to orchestrate resources and services across the domains.

The integration of the virtualized Satellite RAN with the virtualized 5G Terrestrial RAN must achieve the commonality of higher layer functions without sacrificing the performance of the underlaying RANs. Hence, a key research question still to be addressed is to find the right trade-off between harmonization and specialization of network functions for the different terrestrial and satellite domains.

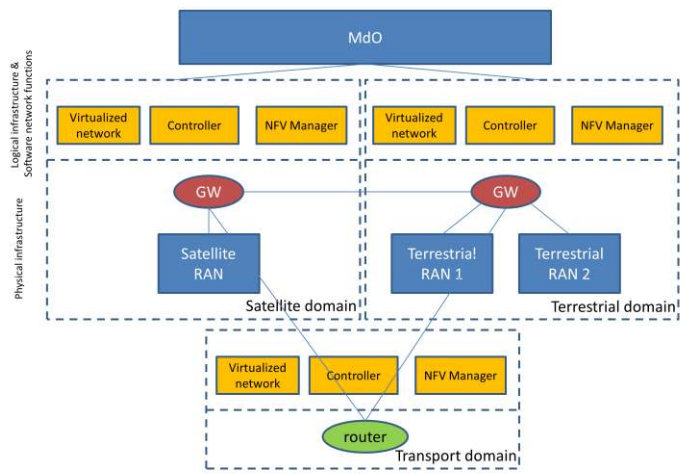


**Fig. 3:** Synthetic view of the terrestrial-satellite integrated architecture according to the 5G SDN/NFV approach.

The user terminal should also simultaneously use the Satellite and the Terrestrial RANs (if simultaneously available) to benefit from the coverage overlap of the two networks for offloading, handover, and multiple path protocols. The coverage overlap will be especially possible in suburban as well as in some urban areas.

The control/user plane latency should be able to cope with large RTT values up to 600 / 180 / 50 ms in the GEO, MEO, and LEO cases, respectively [3]. The user terminal exploiting the Satellite RAN for the forward path and the Terrestrial RAN for the return path can experience reduced RTT values, thus improving the performance (goodput) of all reliable protocols.

*5G integration issues for HTS GEO systems*

HTS GEO systems are expected to provide 5G services with user bit-rates from 25 up to 100 Mbit/s. HTS GEO satellites cannot support extremely low-latency 5G services because of the high round-trip propagation delays. On the other hand, HTS systems are well suited for providing eMBB services. Future HTS will need to adopt flexible payload architectures for performing onboard switching between uplink and downlink beams.

*5G integration issues for LEO/MEO mega-constellations*

LEO/MEO satellites are more suitable than GEO ones for mMTC applications. However, these mega-constellations need complex antenna tracking and double antennas at the earth stations to support a seamless satellite handover procedure. Moreover, mega-constellations with onboard processing can allow the routing in the space. On the other hand, if transparent satellites are adopted, routing is achieved by diverting the traffic to the terrestrial network and using a denser deployment of GWs.

## NETWORK CODING FOR THE PROPOSED INTEGRATED SYSTEM

Network coding allows intermediate nodes in a network (re-)encoding packets that may reach the destination from several neighboring nodes [12]. NC can be used for either increasing reliability or improving the total bandwidth [13]. NC can be implemented as a *shim layer* between transport and network layers so that transport layer can be protected from packet losses and the IP header attached to encoded packets allows routing them inside the network.

In the case of satellite multicast, NC can be employed taking advantage from terrestrial repeaters that can re-encode the multicast data they receive from the satellite; the information coming from the satellite and terrestrial repeaters can be combined to improve the successful delivery.

In future 5G systems, NC should have a corresponding NC virtualization function [13] to facilitate the dynamic adaptation of the NC encoder parameters depending on network and channel measurements and estimations. This approach should also make it possible to transmit coded packets across the domains as considered for the NC technique proposed in the following sub-Section.

### *NC for Multi-path Transmission – Analytical Model*

In a 5G perspective, we consider that a mobile terminal can simultaneously communicate via terrestrial and satellite RANs when coverage overlap is possible. Our NC scheme jointly exploits these two paths that have different characteristics for what concerns propagation delays, capacity, and packet loss rates. Our numerical results are for a GEO scenario, but this study could also be applied to mega-constellations, characterized by multiple satellite visibility; for instance, OneWeb and SpaceX respectively have more than 10 and 100 simultaneously-visible satellites at all latitudes [14].

NC is an efficient approach to exploit multi-path diversity and to protect from packet losses. Our investigation aims to find the optimal conditions to apply NC on top of the IP level and across the two paths [15].

All the traffic flows destined to the same user terminal can be encoded together (inter-flow NC encoder) at an intermediate router (see Fig. 2) that should also be in charge of splitting this traffic via both terrestrial and satellite RANs that are controlled by suitable virtualizations and coordinated using the MdO, as explained in the previous Section. A modified routing table should be used by the intermediate router to support the traffic split via the two paths towards the same destination[1]

We consider a simple case where NC is operated on a block basis for which $R$ redundancy packets are added to $K$ information packets; an encoded block has a size of $N = K + R$ packets. The encoded packets are routed via the satellite path according to the split probability $\alpha$ and via the terrestrial path according to probability $1 - \alpha$. Then, $\alpha N$ [or $(1 - \alpha)N$] encoded packets are sent via the satellite [terrestrial] path characterized by uniform packet losses with rate $p_1$ [$p_2$], where $\alpha N$ is assumed to be an integer number (otherwise a rounded value has to be taken). NC efficiency is $\eta = K/(K + R)$.

The number of packet losses per block on the satellite path is according to a binomial distribution denoted as bino($p_1$, $\alpha N$) and the number of packet losses per block on the terrestrial path is according to a binomial distribution bino($p_2$, $(1 - \alpha)N$). Combining the losses on the two paths, the distribution of the total number of packet losses $P_n$ per encoded block can be expressed as:

$$P_n = bino(p_1, \alpha N) \otimes_d bino(p_2, (1-\alpha)N), \quad n \text{ from 0 to } N \tag{1}$$

where $\otimes_d$ denotes the discrete convolution. This distribution is binomial only if $p_1 = p_2$; otherwise, this is not a classical distribution.

NC can correctly decode a block of $N$ packets received through the two paths if there are up to $R$ packet losses. Then, the success decoding probability $P_s$ can be obtained as:

$$P_s = \sum_{n=0}^{R} P_n. \tag{2}$$

The transport layer goodput (i.e., the amount of correctly-received traffic) for TCP-based traffic can be expressed using $P_s$ and the overall Bandwidth-Delay-Product (BDP) [16] with the two paths combined, that is:

[1] Two independent encoders for the two paths (instead of one across the paths) could also be used; this solution, however, is less efficient than that adopted here and hence it is not considered any further.

$$BDP = \frac{C_1 RTD_1 + C_2 RTD_2}{L}, \quad (3)$$

where $C_1$ and $C_2$ are the capacities of the bottleneck links of path #1 via Satellite RAN and of path #2 via Terrestrial RAN, respectively. Moreover, $RTD_1$ denotes the round-trip propagation delay of path #1 using the Satellite RAN for the forward communication and the Terrestrial RAN for the return communication. $RTD_2$ is the round-trip propagation delay of path #2 via the Terrestrial RAN. Finally, $L$ denotes the packet size in bits.

A block of $N$ packets can be decoded only when at least $K$ independent encoded packets are correctly received through both paths. Then, RTT $\tau$ to deliver an encoded block through the two paths can be characterized as follows:

$$\tau = max\left\{RTD_1 + \left(\frac{B}{2} + N\right)\frac{\alpha L}{C_1}, RTD_2 + \left(\frac{B}{2} + N\right)\frac{(1-\alpha)L}{C_2}\right\} + D_{decoding}, \quad (4)$$

where $B$ denotes the encoder buffer size and $D_{decoding}$ is the NC decoding time according to the model shown in [15]; $B/2$ represents the average number of packets in front of our block of $N$ packets in the encoder buffer.

The goodput maximizes (i.e., we use the two paths optimally) when $\alpha$ allows that the two terms of which we take the maximum in (4) are equal: the traffic loads on the two paths are balanced. This equal-load condition occurs when:

$$\alpha_{opt} = \frac{C_1}{C_1 + C_2} - \frac{RTD_1 - RTD_2}{\left(\frac{B}{2} + N\right) L \left(\frac{1}{C_1} + \frac{1}{C_2}\right)}. \quad (5)$$

It should be noted that the optimal traffic splitting between terrestrial and satellite paths depends on the respective capacity conditions (with related PHY layer modulation and coding scheme) and the different RTD values. When the system settings cause $\alpha_{opt}$ to be close to 0 or 1, it is convenient to use just one path of the two. This approach could be adopted to implement an offloading scheme when the Terrestrial RAN gets congested. From a situation with $\alpha_{opt} = 0$ (because $C_2 >> C_1$: only the terrestrial path is used in non-congested conditions) we could reach a situation of congestion where $\alpha_{opt} > 0$ (because $C_2 < C_1$). Equation (5) will be validated by the goodput results in the next sub-Section.

### *Results*

Figure 4 shows the aggregate goodput (for a TCP-like protocol on top of NC layer) roughly approximated as $BDP \times \eta \times P_s/\tau$ as a function of $\alpha$; several values of the number of redundancy packets $R$ per block from 20 to 43 are considered in order to desensitize the transport layer performance from lower layer packet losses. We assume the following numerical settings: GEO satellite path with $RTD_1$ = 0.255 s (using a terrestrial return path), terrestrial path with $RTD_2$ = 0.01 s, NC block size of $K$ = 50 packets, IP packet size of $L$ = 1500×8 bits, encoder buffer size $B$ = 410 packets, satellite (terrestrial) path bottleneck link capacity $C_1$ ($C_2$) equal to 10 Mbps (5 Mbps), and satellite (terrestrial) path packet loss rate $p_1$ = 0.35 ($p_2$ = 0.2). We consider very high loss rate values to study the performance of TCP-based traffic in the most critical conditions. The results of Fig. 4 show that there is an optimum value of the split probability $\alpha$ [$\alpha_{opt}$ = 0.44] and that there is an optimum number of redundancy packets $R$ per block [$R_{opt}$ = 33 packets and $N$ = 50+33 packets] to maximize the aggregate goodput. The optimal $\alpha$ value shown in the graph is coherent with equation (5) computed for $N$ = 83 packets. If $C_2$ increases (keeping the same $C_1$), the optimal values of both $\alpha$ and $R$ reduce.

The adoption of this optimization approach requires that the intermediate router (applying NC to the traffic flows) receives periodical updates on measurements of $C_1$, $C_2$, $RTD_1$, and $RTD_2$ for each user terminal to update the optimal $\alpha$. The approach expressed by (5) represents a convenient method to determine how to optimally share the traffic load of a TCP-based service on the two paths of an integrated system.

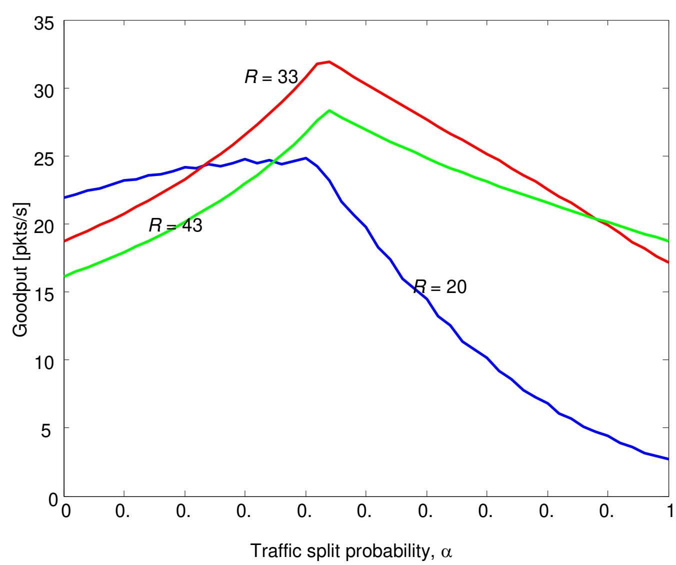


**Fig. 4**: Aggregate capacity of the two paths as seen by TCP as a function of the traffic split probability $\alpha$ with different redundancy settings.

Figure 5 shows the optimum $R$ values (level curves) obtained for the same configuration of $RTD_1$, $RTD_2$, $K$, $L$, $B$, $C_1$, and $C_2$ as for Fig. 4, but varying $p_1$ and $p_2$ packet loss rates on the two paths. We can see that depending on $p_1$ and $p_2$, the optimum $R_{opt}$ values are on a broad range from 5 packets to 40 packets per block. Since in this scenario $C_1$ is close to $C_2$, the variations of $p_1$ and $p_2$ have a similar impact on the selection of the optimum value of $R$. On the other hand, the optimum value of $\alpha$ is almost constant around the 0.44 value for the envisaged range of $p_1$ and $p_2$ values.

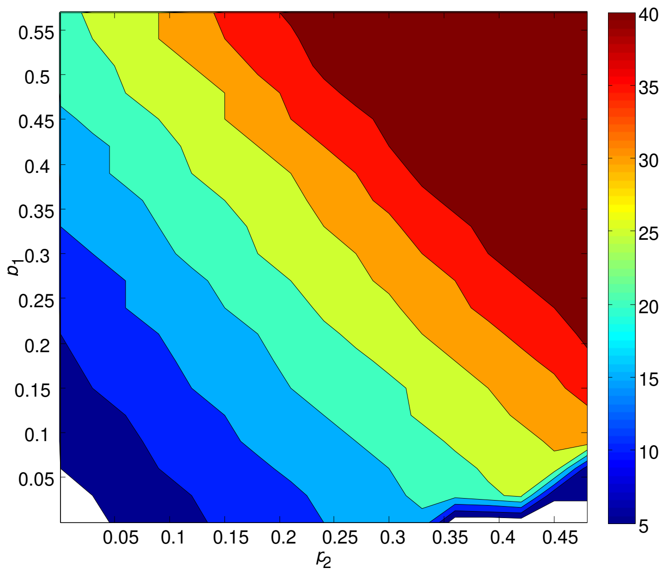


**Fig. 5:** Optimum $R$ values (level curves) for different $p_1$ and $p_2$ values with $K = 50$ pkts.

## CONCLUSIONS

By 2020-2025, many HTS and mega satellite constellations will deliver Terabits of capacity across the world. These systems will provide the 5G Satellite RAN that will be virtualized to facilitate its integration with the 5G terrestrial component. A brief survey of current initiatives and challenges for 5G-satellite integration has been provided. Moreover, we have shown the potentialities for the adoption of NC in future 5G integrated terrestrial and satellite networks, characterized by different propagation delays, capacity, and packet loss rates. In particular, we have proposed an NC-based scheme splitting unicast encoded traffic via satellite and terrestrial domains, showing settings for traffic splitting and redundancy levels to maximize the capacity for TCP-based applications.

Further research is warranted to evaluate the integration options and to study the virtualized functions for the integrated system. Finally, the performance of different network coding approaches must be studied.

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