# HST-NNC: A Novel Hybrid Satellite-Terrestrial Communication With NOMA and Network Coding Systems

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**ABSTRACT** Hybrid satellite-terrestrial networks (HSTNs) are considered to be a promising solution in dealing with coverage and mobility challenges encountered in $5^{th}$ generation (5G) networks that employ novel multiple access and connectivity schemes. In this respect, non-orthogonal multiple access (NOMA) as well as network coding (NC) schemes have attracted significant attention due to their performance gains which not only improve the quality of wireless transmission but also effectively exploit the available spectrum. In this paper, a combined NOMA-NC (NNC) scheme is presented and integrated into an HSTN consisting of a low earth orbit (LEO) satellite belonging to an LEO constellation, a terrestrial base station (BS), and multiple terrestrial mobile terminals (MTs). The proposed scheme, termed HST-NNC (Hybrid satellite terrestrial-NNC), allows pairs of users to be simultaneously served through NOMA via the terrestrial BS link and the satellite link. Furthermore, the satellite employs random linear network coding (RLNC), within the general framework of systematic network coding (SNC), to improve the reception of the MTs when errors occur. The proposed HST-NNC, as compared to standalone NOMA, does not require additional channel state information (CSI) overheads because the satellite needs only the indices of user pairs to perform RLNC. Performance comparisons of HST-NNC with conventional orthogonal multiple access (OMA) and NOMA optimal user pairing schemes have shown that significant sum rate and BER gains can be obtained under various operating system parameters, such as varying number of MTs and different channel conditions.

**INDEX TERMS** BER, hybrid satellite-terrestrial, network coding, NOMA, sum rate.

## I. INTRODUCTION

FIFTH generation (5G) networks aim to support the rapid increase of mobile data traffic for a great variety of applications, ranging from ultra-reliable Internet-of-Things (IoT) applications to broadband multimedia services [1]. It is well-recognized that satellite networks will play an important role in complementing 5G terrestrial networks, e.g., by providing extended coverage and/or increasing the available capacity [2]. It is also well-established that wireless networks based on network coding (NC) and non-orthogonal multiple access (NOMA) have shown tremendous potential for improving the performance of such 5G systems [3], [4].

In the past, NOMA and NC, have been separately applied to satellite communication systems, e.g., see [5], [6], and [7].

In this paper, a novel combined NOMA-NC (NNC) scheme is presented in the context of a hybrid satellite-terrestrial network (HSTN). The proposed scheme allows pairs of users to be simultaneously served through NOMA via the terrestrial base station (BS) link while the satellite employs NC. For the satellite link, it is assumed that it is provided by a low earth orbit (LEO) satellite which is part of an LEO satellite constellation network thus providing continuous coverage in the geographical area covered by the BS.

## A. BACKGROUND

For several years now and from the initial phase of the design of 5G systems, HSTNs have been suggested as a major pillar for enhancing the performance of 5G and beyond networks. Consequently, there have been several publications on this general area of research highlighting the advantages of employing satellites to complement terrestrial communication systems for expanding coverage, improving performance, and increasing their Quality of Service (QoS) provision through network cooperation and enhanced diversity, e.g., see [8], [9]. Within the context of HSTNs, synergies of different wireless communication systems and various access techniques for improved QoS, coverage and load balancing have been proposed, e.g., see [10]. The authors in [11] proposed a cooperative transmission scheme for HSTNs, presenting an energy-efficient radio access network (RAN) by offloading traffic from the terrestrial segment, using a cache-enabled LEO satellite network. The results of this work showed that improved energy efficiency is achieved with a similar traffic offloading performance used in traditional terrestrial systems. Similarly, [12] has developed a traffic offloading scheme that exploits the HSTN system's capabilities to overcome the capacity limitations of the terrestrial backhaul by allocating the traffic between the satellite and the terrestrial segment while satisfying different traffic requirements. Furthermore, the authors in [13] have presented an RAN for integrated satellite-terrestrial networks, proposing a load balancing algorithm, supporting a large number of users, and increasing the network throughput. Moreover, [14] has proposed a relay selection scheme in an HSTN and conducted outage and throughput analysis, considering the effects of hardware impairments and interference on the multi-antenna terrestrial relays and the single-antenna terrestrial user. In another approach, [15] has studied cooperative resource management in spectrum sharing satellite-aerial-terrestrial integrated networks (SATIN), for energy-efficient IoT communications under energy constraints. Meanwhile, as compared to other higher orbit satellite-based architectures and within the context of HSTNs, LEO satellites have been proposed as a viable means for improving connectivity and data offloading with reduced latency [16], [17]. It should be underlined that currently there are significant R&D efforts funded by the high-tech industry towards designing, implementing, and operating advanced integrated satellite and terrestrial networks. Related activities can be found in the forthcoming plans to deploy dense LEO constellations by OneWeb [18] and SpaceX [19] and their plans to cooperate with traditional cellular operators for providing ubiquitous and high QoS communication.

Within this context, the application of NOMA systems in HSTNs has been studied in the past, e.g., see [8], [9] and [20]–[25]. More specifically, [20] presented an HSTN with satellite multicasting in the millimeter waveband and a terrestrial cellular network adopting NOMA in the RF band. Sum rate optimization was formulated under per-antenna transmit power and rate constraints. Computer simulated performance evaluation results have revealed that the proposed system outperforms other NOMA and orthogonal multiple access (OMA) alternatives. In another approach, [21] and [22] designed a channel quality-based scheme allocating users to the satellite and formulating maxmin user pairing in the terrestrial network, thus maximizing the minimum channel correlation between NOMA users of the same group. Also, the satellite-to-terrestrial interference was reduced by using a capacity maximization algorithm under a satellite interference temperature limit. Numerical results have verified the importance of employing a satellite equipped with a large antenna array for improving the overall system capacity.

For networks employing terrestrial relays, [8] studied the outage performance of an HSTN with multiple users by deriving expressions for the exact and asymptotic outage performance. It has also provided performance comparisons with OMA schemes showing the superiority of NOMA for varying number of antennas and fixed power allocation. Furthermore, [9] has dealt with the problem of user cooperation in an HSTN, where the strong user acted as a relay mitigating the impact of heavy shadowing of weak users. For another topology, where a satellite serves multiple users through a terrestrial relay, the impact of outdated channel state information (CSI) has been studied in [23]. Assuming statistical CSI at the transmitters and pilot-based channel estimation at the receivers, a low-complexity iterative power allocation algorithm was presented, minimizing the outage probability of the weakest user. The research in [24] presented a NOMA-based scheme where secondary users coexist with primary users served by an HSTN with a terrestrial relay in a cognitive fashion. Relying on instantaneous CSI, NOMA-based power allocation has been considered for primary-secondary user fairness. Performance comparisons with OMA showed that NOMA can better support the cognitive paradigm in HSTNs. Lastly, [25] has proposed a small-cell hybrid satellite-terrestrial relay system (HSTRS) showing through analysis and computer simulations that, when NOMA is used, the outage performance of HSTRS improves significantly as compared to OMA.

Focusing now on the issue of cooperation between NOMA and NC, which so far has been considered only for terrestrial communications, there have been several papers published in the open technical literature, e.g., [26]–[32]. In particular, [26] presented a multi-user network with an aerial BS developing a novel NNC scheme when CSI at the transmitter is not available. That paper has presented a novel network coded multiple access (NCMA) scheme which allocates equal power to the users' signals with a phase offset, thus providing robustness against dynamic channel conditions, compared to both OMA and NOMA. Furthermore, in [27], a hybrid NNC scheme for two-way relay networks was proposed, addressing mismatches among the size of the two users' bit or symbol sequences due to channel asymmetries in the NOMA scheme when using adaptive modulation and coding. The obtained results have shown that, as compared to

NOMA, hybrid NNC provided improved capacity at a lower complexity. When multiple user pairs communicate through two-way relaying, cooperative NOMA and physical-layer NC (PNC) were jointly considered in [28], adopting the cognitive radio paradigm. More specifically, NOMA ensured the desired rate to the primary pair prior to serving the secondary pair, while PNC combined the users' signals at the relay. As NNC reduced the number of time-slots for end-to-end communication, its advantage over OMA was evident. A network where two users cooperate to transmit towards a single destination was studied in [29]. Both users were equipped with two antennas, performing concurrent reception and transmission, while the destination employed advanced successive interference cancellation (SIC) relying on statistical CSI. Performance evaluation results have shown that NNC benefited both the strong and weak users by reducing their outage performance gap. In [30], groups of users communicating with different destinations through shared relays have been considered. In that paper, a framework combining NOMA and random linear network coding (RLNC)-based relaying was developed. Performance evaluation results have revealed that NOMA with RLNC increased the diversity gain and system throughput, as compared to OMA with RLNC. NOMA-RLNC was also investigated in [31] for multicast downlink services with a single BS, revealing improved total packet success probability and packet delay when NOMA-RLNC is adopted over NOMA. Finally, the work in [32] focused on NOMA-RLNC with BS transmit antenna selection and multicasting to user groups with different rate requirements. By means of computer simulated results it was shown that NOMA-RLNC reduced the transmit power and increased the network throughput when compared to OMA-RLNC.

It is noted that in HSTNs, consisting of an LEO network system providing global coverage and multiple BSs and MTs (e.g., see [34] and [35]), satellite capacity requirements are well within design specifications of state-of-the-art satellites, supporting system applications requiring terabits/sec of satellite capacity (e.g., see [36] and [37]). Still, one of the main challenges in adopting NNC in HSTNs is the effective communication between the terrestrial and the satellite segments. Indeed, the satellite must acquire all the pair indices, i.e., identifying the users comprising each pair, and their corresponding packets to perform NC. As these pair indices must be available to the satellite, together with the corresponding packets, it is convenient that these are provided to the satellite by the core network. Such networking issues present a major challenge for the efficient and effective integration of terrestrial networks with the satellite segment. It should be underlined that various R&D activities in HSTNs are currently under investigation by both academia and industry through projects which are funded by the European Commission, e.g., see 5G Public Private Partnership project Satellite and Terrestrial Network for 5G - "SaT5G" [33]. In addition to these networking issues, for a complete design of an operational HSTN several more challenges exist, e.g.,

performance optimization studies, low-complexity implementation, and launching of LEO constellations, as well as the design and implementation of the MTs' with adequate computational and signal processing capabilities.

## B. CONTRIBUTIONS

As presented in the previous detailed literature review, several works on HSTNs rely on cooperative transmission from the satellite and the BS, both using the NOMA technique. However, such an approach is highly complex, as it requires CSI acquisition and exchange for user pairing and power allocation at both the satellite and the terrestrial links [21], [22]. Meanwhile, other HSTN related works employ terrestrial relays or user cooperation and operate in a multi-hop fashion [9], [24], [25], requiring additional time-slots for end-to-end communication. It is noted that all these approaches are highly complex, e.g., they use beamforming [21] and provide CSI to both terrestrial and satellite links. Consequently, there is a need for a simpler HSTN communication system that will exploit the large coverage area of the satellite segment and improve the communication quality through the effective joint use of the terrestrial-based NOMA and satellite-aided NC. However and to the best of our knowledge, there have not yet been any such studies on NNC systems operating over HSTNs. Motivated by this observation, in this paper, we propose a novel NNC system, operating in conjunction with an HSTN, and as such it will be termed as hybrid satellite-terrestrial NNC (HST-NNC). For this system, the NOMA operation will occur in the terrestrial link, whereas the NC at the satellite. The main contributions of this paper can be summarized as follows:

- The proposed system presents a novel solution for effectively combining the operations of NOMA and NC in a multi-user HSTN environment. Since for the proposed system the satellite performs only NC, it does not require CSI, thus making the HST-NNC much simpler, as compared to other HSTN systems where the satellite is used for NOMA transmission requiring CSI.
- The operation of HST-NNC is presented through an optimization problem. The solution to this problem determines the optimal power allocation of the NOMA transmission for maximizing the sum rate of each user-pair and ensuring that all users enjoy higher rates than those of OMA.
- HST-NNC increases the sum rate and at the same time, reduces the BER, as NOMA improves the terrestrial spectral efficiency while satellite-aided NC reduces the errors occurring during SIC by ensuring partial data recovery and reducing the decoding complexity at MTs.

An important advantage of the proposed HST-NNC, as compared to a standalone terrestrial NOMA scheme, is that it does not incur additional CSI overheads, since the satellite requires only the indices of the user-pairs and not their exact CSI to perform NC. In this way, improved performance is obtained while maintaining low-complexity implementation
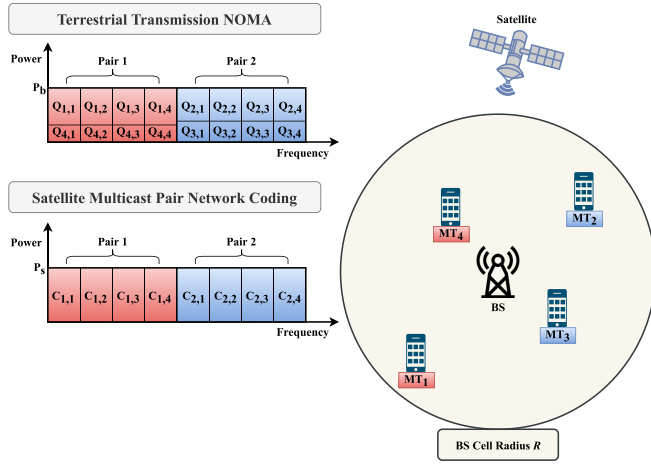
**FIGURE 1.** Resource allocation in the power and frequency domains for an arbitrary time-slot (left) in a topology consisting of 2$K$ MTs ($K = 2$) forming Pair 1: {$MT_1$, $MT_4$} and Pair 2: {$MT_2$, $MT_3$} (right).

for the proposed HST-NNC. In addition, performance evaluation results, comparing HST-NNC with standalone NOMA, employing optimal user pairing [41] and OMA, have revealed its superiority under different operating conditions.

## C. STRUCTURE

The remainder of this paper is organized as follows. In Section II, we introduce the system model and the necessary assumptions for analyzing the communication system under consideration. In Section III, we provide the design of HST-NNC and discuss the details of its operation. Next, various performance evaluation results are presented and discussed in Section IV, while the conclusions and future directions can be found in Section V.

## II. SYSTEM MODEL

### A. TOPOLOGY

As illustrated in Fig. 1, we consider a network consisting of a satellite belonging to an LEO constellation, a BS, and 2$K$ MTs uniformly distributed within the BS coverage area with radius $R$. The satellite is equipped with an antenna having a transmit gain $G_t^s$ and total available transmit power $P_s$ with downlink frequency $f_s$ and bandwidth $B_s$. Furthermore, the BS has a single antenna with transmit gain $G_t^b$ and total available transmit power $P_b$. The operating frequency for the terrestrial links, i.e., between BS and MTs, is denoted as $f_b$ and the total available bandwidth as $B_b$. Each $MT_k$ ($1 \leq k \leq 2K$) has two antennas, one for the reception of the satellite signal with a reception gain, denoted as $G_r^s$, and another for the reception of the BS signal with a reception gain, denoted as $G_r^b$. It is noted that the terrestrial and satellite signals are simultaneously received by the MTs over two separate non-overlapping spectrum bands. Similar to [34] and [35], it is assumed that the satellite and BS can communicate via the backbone network and that both have perfect knowledge of all the packets transmitted to the MTs. For the terrestrial transmission strategy, we consider $K$ pairs of

users, where each pair, has a strong and a weak user. The classification of these two users is based upon the strength of the received signal and depends on the channel conditions between the BS and the MTs. Let us now consider the example of two pairs of users as shown in Fig. 1, where the Q's and C's denote the original and the coded packets transmitted from the BS and the satellite, respectively. As it will be explained in the detailed operation of the proposed system, on the one hand, for the terrestrial NOMA transmission (see Section III-A), the upper row of the Q's denotes the signal power allocation to the weak users whereas the lower row denotes the signal power allocation to the strong users. On the other hand, for the satellite-aided NC transmission (see Section III-B), the C's are multicast to each pair of MTs.

In other words, the MTs are served through an HSTN with the BS providing the primary communication link, whereas the satellite is employed to improve the overall communication quality. The proposed transmission scheme relies on simultaneous BS-satellite transmission, occurring over two different spectrum bands. The BS employs power-domain NOMA with optimal user pairing, transmitting its data to the MT pairs using superposition coding. The transmission from the BS and the satellite to the MTs is packet-based. At the same time, the satellite transmits coded packets to each pair of MTs using RLNC and OMA, multicasting the packets of the weak MT of each pair. Essentially, based on the NOMA principle, for each user pair, the weak user directly demodulates the coded BS signal in the power domain and retrieves its own original packets. On the other hand, the strong user first demodulates the coded BS signal in the power domain, then retrieves the original packets of the weak user, and finally performs SIC to retrieve its own original packets. Therefore, both users in each pair are aware of the weak users' original packets. Based on this fact and the NC principle, the satellite multicasts to each pair coded packets from the weak user's original packets using RLNC.

For each pair, the weak MT uses both coded and original packets that are correctly received from the satellite and the BS, retrieving its own original packets without errors. Furthermore, the strong user exploits both coded and original packets that are correctly received from the satellite and the BS, respectively, regenerating the weak user's signal correctly and performing perfect SIC for decoding the strong user's data with reduced errors. It is noteworthy, that the strong user will achieve perfect SIC, if and only if, it receives the weak user's signal correctly. Otherwise, the strong user estimates the weak user's signal and performs imperfect SIC.

### B. CHANNEL MODEL

The communication channel between the satellite and the MTs is modeled according to the Loo's fading model [38]. For this model, the power of the line of sight (LOS) component is log-normally distributed with parameters $(\alpha, \psi)$, while the power of the multipath component (MP) follows the Rayleigh distribution with complex channel

coefficients, denoted as $h_k^s$ for each $MT_k$, assuming zero mean and variance $\sigma_c = \sqrt{0.5 \cdot 10^{\frac{MP}{10}}} \sim \mathcal{N}(0, \sigma_c^2)$. Furthermore, a maximum Doppler shift of 40 $kHz$ is assumed and modeled with the Jakes model [39]. In addition to fading, we have considered pathloss attenuation denoted as $L_{FS_k}$ for each $MT_k$, using the free space pathloss (FSL) model.

As far as the terrestrial links are concerned, the multipath fading is modeled by the Rayleigh distribution with zero mean and unit variance $\sim \mathcal{N}(0, 1)$. The channel complex coefficients are $h_k^b$ for each $MT_k$. The pathloss attenuation of the BS's signal, $PL_k$, is modeled using the COST231 pathloss model in an urban micro environment. The MTs move within the BS cell radius at a constant speed of $V_{MT} = 3$ $km/hr$.

Both satellite and terrestrial links are degraded by additive white Gaussian noise (AWGN) $\sim \mathcal{N}(0, \sigma_d^2)$ with $d = \{s, b\}$. The noise powers at the receiver equipment for the satellite signal and for the terrestrial signal are calculated as $N_s = \kappa T_s B_s$ and $N_b = \kappa T_b B_b$, respectively, where $T_s$ and $T_b$ represent the corresponding system noise temperatures and $\kappa$ is the Boltzmann constant. Thus, the corresponding variances for each receiver type are $\sigma_s = \sqrt{N_s}$ and $\sigma_b = \sqrt{N_b}$.

### C. TRANSMISSION PARAMETERS

Regarding the terrestrial transmission, if the BS employs OMA, each $MT_k$ will receive $n$ original packets amounting to $b$ bits in a time-slot. Each original packet is represented by $Q_{k,v}$ ($1 \leq v \leq n$). The number of symbols that each $MT_k$ will receive in a time-slot is $l = b/\log_2(M)$, where $M$ is the modulation order and the symbol sequence for each $MT_k$ is represented as $s_{k,1\ldots l}^b$. Then, the number of symbols per packet is $l/n$ and the total number of symbols transmitted from the BS in a time frame is $2Kl$. On the other hand, if the BS uses NOMA combined with a user pairing scheme, for fairness it is assumed that each MT will again receive $n$ packets. However, in this case, the total number of bits per user is $2b$, the bits per packet is $2b/n$, the symbols per packet are $2l/n$, while the total transmitted symbols remain $2Kl$. It can be easily deduced that, for the same bandwidth, as compared to OMA, by employing NOMA the MTs will receive more symbols.

In the satellite-aided NC transmission, the satellite multicasts to each pair of MTs, $p$ ($1 \leq p \leq K$), $n$ coded packets based on RLNC, where each packet is represented as $C_{p,v}$ ($1 \leq v \leq n$). The number of coded packets equals to the number of the original packets that are sent from the BS, having the same length. Essentially, the coded packets for each pair of MTs are linear combinations of the original packets of the weak user from each pair. The technique of transmitting the original packets through one link and coded packets through another link is referred as systematic network coding (SNC) [40]. SNC ensures partial data recovery, while reducing the decoding complexity, because the more original packets that will be correctly received from one link known to the system, the lesser the time that will be consumed during the decoding procedure.

In summary, in the proposed HST-NNC, each $MT_k$ receives $n$ original packets from the BS and $n$ coded packets from the satellite. Therefore, each $MT_k$ receives $2n$ packets in total, and thus at least $n$ error-free original or coded packets are needed to retrieve the information data without errors as the proper operation of RLNC requires the solution of a set of $m$ equations with $n$ unknown variables, where $m \geq n$.

## III. HST-NNC
### A. TERRESTRIAL NOMA TRANSMISSION

Here, perfect CSI of the terrestrial links is assumed, relying on pilot transmissions from the BS to the terrestrial MTs, and subsequently, channel quality is reported from the latter to the former. A similar procedure has been followed in other relevant works, such as [20], [21], [24]. More specifically, each $MT_k$ ($1 \leq k \leq 2K$) reports its CSI to the BS which is equal to the mean value of complex power channel coefficients $\overline{|h_k^b|^2}$, and thus for each user $MT_k$ its channel gain $\Gamma_k$ can be obtained as follows:

$$\Gamma_k = \frac{G_t^b G_r^b}{PL_k N_b} \overline{|h_k^b|^2}. \tag{1}$$

Next, the BS should create $K$ pairs of users in total, where each pair will share the same sub-channel in the power and time domains with different power allocation factors of the total BS power $P_b$. If the BS uses a conventional OMA technique in the time domain the theoretical achievable rate of each $MT_k$ can be expressed as:

$$R_k^{OMA} = \frac{1}{2K} B_b \log_2(1 + P_b \Gamma_k). \tag{2}$$

On the contrary, in the case of an NOMA optimal user pairing scheme, the goal is to identify appropriate pairs of users that maximize the total sum rate. Thus, let us assume that users $MT_i$ and $MT_j$ form a pair, with $\Gamma_i \leq \Gamma_j$, and they share the same sub-channel in the power and time domains. The achievable rates for the weak user, $MT_i$, and the strong user, $MT_j$, are given by:

$$R_j^{NOMA(i,j)} = \frac{1}{K} B_b \log_2\big(1 + \beta_j P_b \Gamma_j\big), \tag{3}$$

$$R_i^{NOMA(i,j)} = \frac{1}{K} B_b \log_2\bigg(1 + \frac{\beta_i P_b \Gamma_i}{\beta_j P_b \Gamma_i + 1}\bigg), \tag{4}$$

respectively, where $\beta_j$ is the power allocation factor of the strong user and $\beta_i = 1 - \beta_j$ is the power allocation factor of the weak user, with $\beta_j \leq \beta_i$. The optimal value of $\beta_j$ which maximizes the sum rate for this pair of users and at the same time ensures that both users enjoy at least the rate provided by standalone OMA, can be obtained by solving the following maximization problem:

$$\max_{\beta_j} \quad R_i^{NOMA(i,j)} + R_j^{NOMA(i,j)},$$
$$\text{s.t.} \quad R_i^{NOMA(i,j)} \geq R_i^{OMA},$$
$$R_j^{NOMA(i,j)} \geq R_j^{OMA},$$
$$0 \leq \beta_j \leq 1. \tag{5}$$

The solution to this problem has been obtained in [41] by identifying the optimal value of $\beta_j$, $\beta_j^*$, as:

$$\beta_j^* = \frac{\sqrt{1 + \Gamma_i P_b} - 1}{\Gamma_i P_b}. \tag{6}$$

It was further shown in [41] that, when the system consists of $2K$ MTs and in order to guarantee that the system sum rate will be optimal, the $MT_k$ should be paired with the $MT_{2K-k+1}$ and solve the maximization problem (5) for each such pair of users, for $\Gamma_1 \leq \Gamma_2 \leq \ldots \leq \Gamma_{2K}$. In this way, the BS creates $K$ pairs of users and for each such pair the corresponding power allocation factor $\beta_{2K-k+1}$ for the strong user is calculated using (6) while for the weak user it is $\beta_k = 1 - \beta_{2K-k+1}$. Consequently, channel asymmetries are optimally exploited, improving the chances for successful SIC. Moreover, HST-NNC guarantees that the rate of each user will not fall below that of standalone OMA, thus ensuring user fairness.

Afterwards, the BS using superposition coding adds the $MT_i$ and $MT_j$ modulated signals $S_i^b$ and $S_j^b$, for each pair of users $(i, j)$, with $\Gamma_i \leq \Gamma_j$ and transmits the coded signal in the power domain as:

$$x_b^{(i,j)} = \sqrt{G_t^b}\left(\sqrt{\beta_j P_b}S_j^b + \sqrt{\beta_i P_b}S_i^b\right). \tag{7}$$

Then, $MT_i$ and $MT_j$ receive the BS signal:

$$y_i^b = \sqrt{\frac{G_r^b}{PL_i}}h_i^b x_b^{(i,j)} + z_n^b, \tag{8}$$

$$y_j^b = \sqrt{\frac{G_r^b}{PL_j}}h_j^b x_b^{(i,j)} + z_n^b, \tag{9}$$

respectively, where $z_n^b$ is the AWGN noise in the terrestrial link.

Subsequently, the weak user, $MT_i$, and the strong user, $MT_j$, directly demodulate the corresponding received BS signal, and thus both receive the symbol sequence $s_{i,1\ldots l}^b$ and the packets $Q_{i,1\ldots n}$ of the weak user. Therefore, both of these MTs identify the number of successfully received packets, $L_Q$, of the weak user. Note that, $Q_{k,1\ldots n}$ represents the $n$ packets sequence received from $MT_k$, while $s_{k,1\ldots l}^b$ is the symbol sequence that $MT_k$ will receive in a time-slot from the BS.

### B. SATELLITE-AIDED NETWORK CODING TRANSMISSION

During this transmission, the satellite employs RLNC creating $n$ coded packets for each pair of MTs as linear combinations of the original packets of the weak user from each pair via a coefficient matrix $G_{nXn}^k$ with randomly chosen $g_{1\ldots n,1\ldots n}^k$ coefficients over the Galois Field (GF) with size $2^w$. The number of rows equals to the number of coded packets and the number of columns equals to the number of original packets. Mathematically the coding operation can be expressed as:

$$\begin{bmatrix} C_{k,1} \\ C_{k,2} \\ \vdots \\ C_{k,n} \end{bmatrix} = \begin{bmatrix} g_{1,1}^k & g_{1,2}^k & \cdots & g_{1,n}^k \\ g_{2,1}^k & g_{2,2}^k & \cdots & g_{2,n}^k \\ \vdots & \vdots & \ddots & \vdots \\ g_{n,1}^k & g_{n,2}^k & \cdots & g_{n,n}^k \end{bmatrix} \begin{bmatrix} Q_{k,1} \\ Q_{k,2} \\ \vdots \\ Q_{k,n} \end{bmatrix}. \tag{10}$$

After that, the satellite creates and modulates the symbol sequence $s_t^s = \{C_{t,1}, C_{t,2}, \ldots, C_{t,n}\}$ for each pair of MTs based on the weak users' original packets, in $S_t^s$, and transmits the total signal $x_t^s$ using OMA. Each $MT_i$ and $MT_j$ that form a pair receives the multicast signal in a time-slot $t$ allocated for this pair from the satellite:

$$y_i^s = \sqrt{\frac{G_r^s}{L_{FS_i}}}h_i^s x_t^s + z_n^s, \tag{11}$$

$$y_j^s = \sqrt{\frac{G_r^s}{L_{FS_j}}}h_j^s x_t^s + z_n^s, \tag{12}$$

respectively, where $z_n^s$ stands for the AWGN noise in the satellite link.

The strong and the weak user of each pair, $MT_j$ and $MT_i$, respectively, demodulate the received signal from the satellite retrieving the symbol sequence $s_t^s$ and the coded packets $\{C_{t,1}, C_{t,2}, \ldots, C_{t,n}\}$, and calculate the number of correctly received coded packets $L_C$. If $L_Q + L_C \geq n$, then $MT_i$ can retrieve all the original packets without errors. Otherwise, it calculates the errors based on the packets received from the BS. For $MT_j$, if $L_Q + L_C \geq n$, it can regenerate the original signal of the weak user and perform perfect SIC to estimate its own signal $\hat{S}_j^b$ as:

$$\hat{S}_j^b = y_j^b - \sqrt{\frac{\beta_i P_b G_t^b G_r^b}{PL_j}}h_j^b S_i^b. \tag{13}$$

Otherwise, $MT_j$ should estimate the weak user's signal based on the received BS signal and perform imperfect SIC.

$$\hat{S}_j^b = y_j^b - \sqrt{\frac{\beta_i P_b G_t^b G_r^b}{PL_j}}h_j^b \hat{S}_i^b, \tag{14}$$

where $\hat{S}_i^b$ is the estimated signal of the weak user at the strong user. There are three different cases where the MTs receive the original packets error-free which require different decoding procedures as follows:

1) *Reception of the original packets:* In this case, as the original packets have been received no further action is needed.

2) *Reception of the coded packets:* In this case, each $MT_k$ can retrieve the original packets by performing the following operation in GF:

$$\begin{bmatrix} Q_{k,1} \\ Q_{k,2} \\ \vdots \\ Q_{k,n} \end{bmatrix} = \begin{bmatrix} g_{1,1}^k & g_{1,2}^k & \cdots & g_{1,n}^k \\ g_{2,1}^k & g_{2,2}^k & \cdots & g_{2,n}^k \\ \vdots & \vdots & \ddots & \vdots \\ g_{n,1}^k & g_{n,2}^k & \cdots & g_{n,n}^k \end{bmatrix}^{-1} \begin{bmatrix} C_{k,1} \\ C_{k,2} \\ \vdots \\ C_{k,n} \end{bmatrix}. \tag{15}$$

---

**Algorithm 1** HST-NNC

1: **input** CSI for $MT_k$, $k = 1, 2, \ldots, 2K$
2: Sort MTs in ascending order based on their CSI values, and calculated $\Gamma_k$.
3: Pair user $MT_k$ with user $MT_{2K-k+1}$ and for each pair calculate the optimal power allocation factor $\beta_{2K-k+1}$ through (6) using $\Gamma_k$ and $\beta_k = 1 - \beta_{2K-k+1}$.
4: Create the coded signal in power domain for each pair of users as in (7).
5: Find the original packets $Q_{k,1\ldots n}$ correctly received at $MT_k$ and $MT_{2K-k+1}$, and determine $L_Q$ for each user.
6: Receive satellite signal and find the coded packets $C_{k,1\ldots n}$ correctly received to determine $L_C$ for each user in pair.
7: **if** $L_Q + L_C < n$ **then**
8:     Weak user $MT_k$ calculates the errors by comparing them to the original packets.
9:     Strong user $MT_{2K-k+1}$ estimates weak user's signal, performs imperfect SIC based on (14) in order to retrieve the strong user's packets and calculate the errors.
10: **else**
11:     **if** $L_Q = n$ **then**
12:         All the original packets are correctly received.
13:     **else**
14:         Each MT uses the original correctly received packets and the minimum required coded packets, solves the system and obtains the weak user's original packets.
15:     **end if**
16:     $MT_k$ obtain the error-free data.
17:     $MT_{2K-k+1}$ knows the weak users' signal and performs perfect SIC based on (13) in order to retrieve its own packets and calculate the errors.
18: **end if**
19: **output** BER for $MT_k$, $k = 1, 2, \ldots, 2K$ and Maximum Sum Rate.

---

3) *Reception of a combination of coded and original packets:* In this case, each $MT_k$ receives a combination of coded and original packets which will be jointly used to obtain the original packets. For example, if we assume the total number of original packets are three, $MT_k$ correctly receives two coded packets $C_{k,2}$ and $C_{k,3}$ and one original packet $Q_{k,1}$. Thus, $MT_k$ can retrieve the original packets as:

$$\begin{bmatrix} Q_{k,1} \\ Q_{k,2} \\ Q_{k,3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ g_{2,1}^k & g_{2,2}^k & g_{2,3}^k \\ g_{3,1}^k & g_{3,2}^k & g_{3,3}^k \end{bmatrix}^{-1} \begin{bmatrix} Q_{k,1} \\ C_{k,2} \\ C_{k,3} \end{bmatrix} \quad (16)$$

Otherwise, if $L_Q + L_C < n$ the $MT_k$ has only the number of original packets that are correctly received.

The above described decoding procedures together with the detailed operation of the proposed HST-NNC system can be found in Algorithm 1.

## C. COMPLEXITY ANALYSIS

As previously explained, HST-NNC requires the acquisition of the CSI for the terrestrial channel between the BS and the MTs. Furthermore, in order to form pairs of users for the NOMA terrestrial transmission, the BS first sorts the MTs in ascending order based on their channel gains obtained by the CSI with time complexity $O(N \log N)$, where $N = 2K$ represents the total number of MTs. Then, in linear time $O(N)$, the BS forms pairs of users $[MT_k; MT_{2K-k+1}]$ $\forall k \in \{1, 2, \ldots, K\}$, calculates the optimal power allocation for each pair and performs NOMA transmission in the power domain. On the other hand, the satellite simply needs to know the formed pairs of users without requiring any CSI for the satellite to MTs links. This information can be easily provided from the BS to the satellite by the core network essentially without increasing the overall complexity. However, as compared to standalone NOMA schemes, there will be a small increase in the complexity of the HST-NNC, which is due to the decoding of the NC packets transmitted from the satellite to the MTs.

## IV. PERFORMANCE EVALUATION
### A. SYSTEM SETUP

In this section, simulations results are presented in terms of sum rate and bit error rate (BER) for different system parameters and transmission techniques. Regarding the wireless channel conditions, the Loo's model channel parameters ($\alpha$, $\psi$, $MP$) have been selected for an urban area, operating in the L-Band, where MTs are equipped with handheld antennas, based on the information given in [42, Table XIII]. Specifically, we consider the cases of weak channel (WC) where users experience deep shadowing, medium channel (MC), corresponding to an intermediate shadowing state and strong channel (SC), representing the Line of Sight (LoS) case. We examine the cases that all MTs experience the same channel conditions WC, MC or SC for different values of the elevation angle $20°$, $40°$ and $60°$ degrees. Furthermore, we consider an average range $R_s = 1700$ km when $E = 20°$, $R_s = 1000$ km when $E = 40°$ and $R_s = 900$ km for the case of $E = 60°$ between each MT and the satellite. Table 1 includes the simulation parameters that have been used for the performance evaluation. The simulation parameters regarding the LEO satellite as well as the terrestrial satellite receivers are based on the parameters of the Iridium system as presented in [43]. The terrestrial path-loss model that is used is the COST231-Walfisch-Ikegami [44], in an urban micro environment [45]. Furthermore, the Galois field size is selected based on [46]. Finally, the simulation parameters regarding the terrestrial communication (BS and MTs) are selected based on [47].
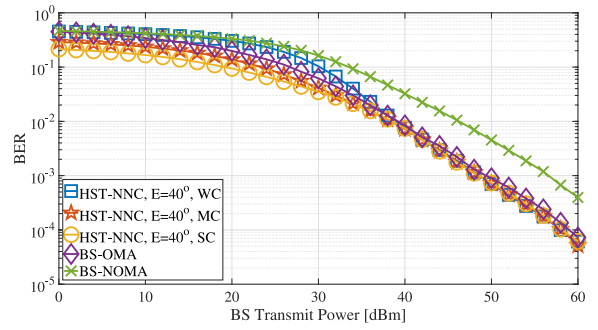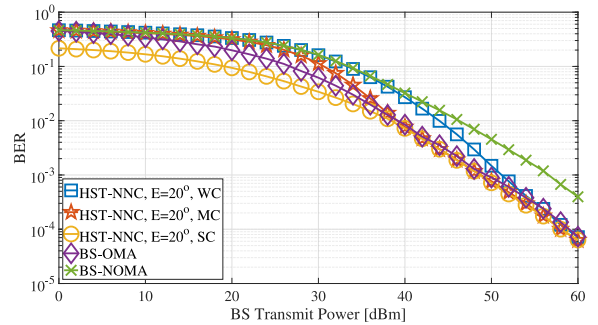
### B. COMPARISONS

Comparisons are performed between the proposed HST-NNC technique and the standalone NOMA [41] with optimal user pairing but without NC, as well as with the standalone OMA.

**TABLE 1.** Simulation parameters.

| Bits per MT per time-slot OMA | 1000 |
|---|---|
| Bits per MT per time-slot NOMA | $2 \cdot 1000 = 2000$ |
| Packets per MT | 20 |
| Time-slot length | 10 ms |
| Channel Bandwidth | 50 kHz |
| Simulated frames | 100000 |
| Modulation scheme | QPSK |
| Phase offset | $\pi / 4$ |
| Symbol order | Gray |
| Satellite antenna gain $G_t^s$ | 24.3 dBi |
| Satellite downlink frequency $f_s$ | 1.625 GHz |
| Satellite transmit power $P_s$ | 43 dBm |
| Bandwidth $B_d$ with $d = \{s, b\}$ | 5 MHz |
| System receiver $T_s$ | 25.7 dBK |
| Receiver antenna gain $G_r^s$ | 2.7 dBi |
| BS antenna gain $G_t^b$ | 5 dBi |
| BS operating frequency $f_b$ | 2 GHz |
| BS cell radius $R$ | 500 m |
| BS transmit power $P_b$ | 0-60 dBm |
| System receiver $T_b$ | 24.7 dBK |
| Receiver antenna gain $G_r^b$ | 0 dBi |
| Terrestrial pathloss model | COST231-Walfisch-Ikegami |
| Terrestrial pathloss environment | urban micro |
| Galois field size $2^w$ | $w = 8$ |
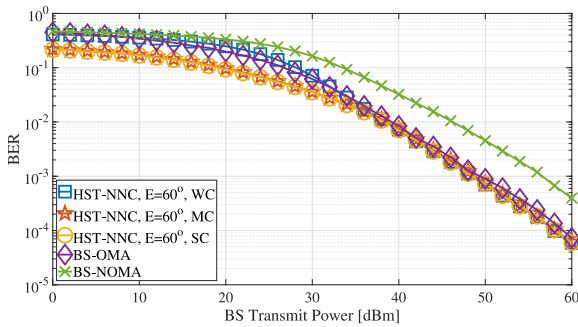


**FIGURE 2.** Average BER for 64 MTs and different channel conditions with *E* = 60° for different values of BS transmit power.



**FIGURE 3.** Average BER for 64 MTs and different channel conditions with *E* = 40° for different values of BS transmit power.



**FIGURE 4.** Average BER for 64 MTs and different channel conditions with *E* = 20° for different values of BS transmit power.

In Fig. 2, BER performance comparisons between HST-NNC, BS-NOMA and BS-OMA are presented, for a network consisting of 64 MTs, $E = 60°$ and operating under different channel conditions. Under MC and SC conditions, HST-NNC outperforms BS-NOMA, by yielding a significant performance gain as compared to standalone NOMA without NC throughout the BS transmit power range. Under the same channel conditions, the proposed scheme outperforms BS-OMA for transmit power levels ranging from 0 to 38 dBm. HST-NNC has better performance than NOMA when MTs operate in WC conditions at low–medium BS transmit power values. Additionally, for medium–high BS transmit power values, it can be observed that HST-NNC performance under WC conditions is superior to that of NOMA with optimal user pairing and without the satellite segment. Furthermore, for the same BS transmit power levels and channel conditions, the proposed technique behaves better than BS-OMA. Regarding the BER comparison between BS-NOMA and BS-OMA, it can be observed that these results comply with the findings in [48].

In Fig. 3, BER performance comparisons between HST-NNC, BS-NOMA and BS-OMA are presented, for a network consisting of 64 MTs, $E = 40°$ and operating under different channel conditions. Again, HST-NNC under MC and SC conditions surpasses the BS-NOMA technique, offering notable performance gains as compared to NOMA without NC throughout the BS transmit power range. It is noted that under the same channel conditions the HST-NNC behaves much better than the BS-OMA technique for transmit power levels ranging from 0 to 38 dBm. Furthermore, HST-NNC offers slightly better BER performance than NOMA when MTs experience WC channel conditions at low BS transmit power values. At medium–high BS transmit power values, it can be seen that HST-NNC under WC conditions outperforms the NOMA case where the satellite segment is missing, while offering marginally better performance than BS-OMA.

In Fig. 4, BER comparisons are shown for a network with 64 MTs and $E = 20°$. Here, it is observed that HST-NNC under SC conditions exhibits the best performance up to a power level of 36 dBm. At low–medium values of the BS transmit power and under WC and MC channel conditions, NOMA and HST-NNC have very similar performance, while OMA achieves better results. Moreover, in the case of MC at medium–high BS transmit power values, HST-NNC achieves better results, compared to the standalone OMA and NOMA with optimal user pairing. It is noted that OMA and HST-NNC exhibit similar BER performance at power levels
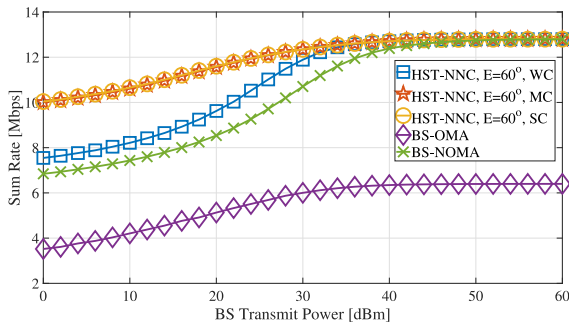
**FIGURE 5.** Sum rate for 64 MTs and different channel conditions with $E = 60°$ for different values of BS transmit power.
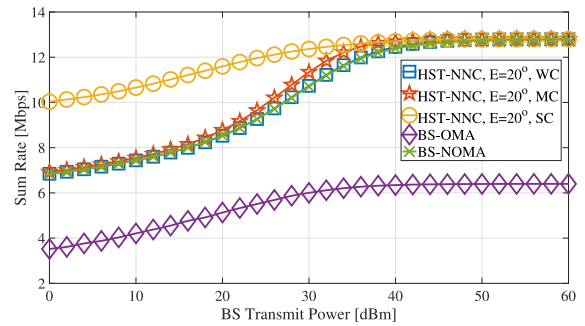


**FIGURE 7.** Sum rate for 64 MTs and different channel conditions with $E = 20°$ for different values of BS transmit power.
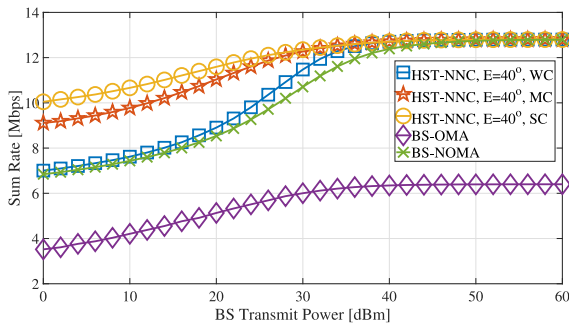


**FIGURE 6.** Sum rate for 64 MTs and different channel conditions with $E = 40°$ for different values of BS transmit power.
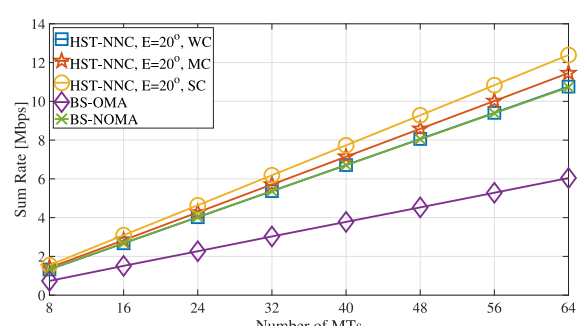


**FIGURE 8.** Sum rate for varying number of MTs and different channel conditions with $E = 20°$ for BS transmit power value equal to 30 dBm.



**FIGURE 9.** Sum rate for varying number of MTs and different channel conditions with $E = 60°$ for BS transmit power value equal to 30 dBm.

above 40 dBm, while under deep shadowing the performance is improved at higher BS transmit power values.

In Fig. 5, comparisons in terms of total sum rate are shown, for a network with 64 MTs communicating with the satellite at $E = 60°$ in HST-NNC. It can be seen that for this elevation angle value and independently of the satellite channel condition, HST-NNC's performance exceeds that of the other schemes for low–medium BS transmit power values. Specifically, when MTs experience MC and SC conditions, similar sum rate is provided. At high BS transmit power values, there are not noteworthy differences between HST-NNC and NOMA. In addition, in the whole range of BS transmit power values, standalone NOMA and HST-NNC are superior to OMA.

Fig. 6 includes sum rate comparisons for a topology with 64 MTs communicating at $E = 40°$ with the satellite and different channel conditions in HST-NNC. HST-NNC under MC and SC conditions outperforms NOMA and OMA without NC from the satellite part throughout the BS transmit power range. In addition, HST-NNC performs better than NOMA when MTs operating under WC conditions at low BS transmit power values. At medium–relatively high BS transmit power values, it is seen that HST-NNC with WC conditions outperforms NOMA with optimal user pairing.

In Fig. 7, sum rate comparisons of HST-NNC with 64 MTs, $E = 20°$ and different channel conditions, as well as NOMA and OMA relying only on the terrestrial BS are shown. Here, it is noteworthy that compared to NOMA, HST-NNC offers significantly better sum rate when MTs
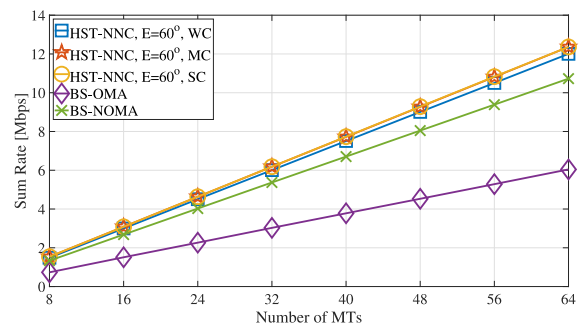
experience SC conditions, slightly better sum rate under MC conditions and almost identical sum rate under WC conditions.

In Fig. 8, the sum rate performance is illustrated, for a network with varying number of MTs communicating with the satellite at $E = 20°$ in HST-NNC and $P_b = 30$ dBm regarding the BS transmit power. It can be observed that for all channel condition cases HST-NNC and BS-NOMA outperform BS-OMA, while HST-NNC for SC and MC provides significantly higher sum rate than BS-NOMA. At the same time, compared to BS-NOMA, the proposed scheme has almost identical performance under WC conditions.

Fig. 9 shows sum rate comparisons for varying MT number communicating at $E = 60°$ with the satellite and different channel conditions in HST-NNC, with BS transmit power

$P_b = 30$ dBm. HST-NNC independently of satellite channel conditions surpasses the sum rate of NOMA and OMA without satellite-aided NC. More specifically, as the number of MTs increases, the performance gap of HST-NNC and BS-NOMA increases. This can be explained by the fact that as the diversity of the channel conditions of terrestrial users increases, the performance of the NOMA optimal user pairing technique is enhanced. Further improvements are achieved by the use of the NC technique by satellite.

### C. LESSONS-LEARNED
Based on the performance evaluation results, some conclusions can be drawn for the application of HST-NNC, in hybrid satellite-terrestrial networks.

At first, HST-NNC is an attractive solution when MTs communicate with the satellite at $40° \leq E \leq 60°$ under SC and MC conditions, independently of the BS transmit power. Figs. 2 and 3 show that under SC and MC conditions, BER gains are particularly high compared to BS-NOMA without NC. At the same time, from Figs. 5 and 6, for low–medium BS transmit power, the sum rate of HST-NNC is significantly higher than that of BS-NOMA and BS-OMA. Then, for high BS transmit power sum rate is the same for all the schemes, but BER is improved, thus reducing retransmissions in the network.

It is further noted that, HST-NNC can be adopted when MTs communicate with the satellite at $E = 60°$ under WC conditions for varying BS transmit power. Figs. 2 and 5 indicate performance gains compared to BS-NOMA. Again, for high BS transmit power, sum rate gains are negligible, but BER results are much better. In case of $E = 40°$ under WC conditions and low BS transmit power, HST-NNC BER and sum rate are equal to BS-NOMA, as shown in Figs. 3 and 6. Performance gains are achieved for medium–high BS transmit power, mostly for BER. Thus, for $E = 40°$ and under WC conditions, HST-NNC is useful for high BS transmit power to improve BER and medium–high BS transmit power to improve both BER and sum rate.

Moreover, the obtained performance evaluation results have clearly shown the importance of the satellite segment when MTs communicate at $E = 20°$ under SC conditions, as observed in Figs. 4 and 7. In the case of $E = 20°$ under MC conditions and for low–medium BS transmit power, HST-NNC BER and sum rate gains are negligible, as shown in Figs. 4 and 7, respectively. HST-NNC performance improves for medium–high BS transmit power. Therefore, HST-NNC can be beneficial for $E = 20°$ under MC conditions and high BS transmit power to improve BER and at medium–high transmit power to improve both metrics.

Finally, for $E = 20°$ and WC conditions, as illustrated in Fig. 7 no difference is observed between the sum rate of HST-NNC compared to BS-NOMA independently of the BS transmit power. Also from Fig. 4 for the same elevation angle and channel conditions, BER differences are observed for BS transmit power above 40 dBm. Therefore, in this case, it is reasonable to only use HST-NNC at high BS transmit power values in order to improve the BER performance and reduce the number of retransmissions.

## V. CONCLUSION AND FUTURE DIRECTIONS
### A. CONCLUSION
Hybrid satellite-terrestrial networks can improve the communication quality in highly challenging scenarios, where connectivity is threatened. Since various novel transmission and multiple access schemes have been recently introduced for 5G networks, there is high potential in integrating them within HSTNs. This paper has proposed a novel scheme, termed HST-NNC, which effectively combines the NOMA and NC techniques in the context of HSTNs. The detailed operation of this scheme has been presented and its performance has been evaluated through extensive computer simulations. Performance comparisons with OMA and NOMA without NC outlined the gains of HST-NNC, in terms of BER and sum throughput for different system parameters and under various operating and channel conditions.

### B. FUTURE DIRECTIONS
There are several interesting directions where HST-NNC can be extended as follows:

- Recently, grant free NOMA transmission has been shown to further reduce the signaling overhead of the terrestrial segment [49]. Adapting HST-NNC for grant free NOMA communication will facilitate massive connectivity in 5G and beyond scenarios.
- Integrating artificial intelligence and machine learning will allow fully autonomous zero-touch satellite-terrestrial communication [50], [51].
- Rate splitting represents a generalized technique encompassing NOMA and OMA [52]. At the same time, using hybrid NOMA/OMA can further increase the sum throughput, as it has been shown for terrestrial networks [53], [54]. Such flexible schemes are viable ways of improving the performance of satellite-terrestrial networks.
- A proactive caching approach can be studied for effective content dissemination to users of hybrid satellite-terrestrial networks, significantly offloading the terrestrial segment [55].
- Another important aspect of HSTNs that should be further studied is the optimization of the handover procedure among the LEO satellites of the constellation, in order to support the terrestrial segment and avoid performance degradation of the NNC transmission [56], [57].

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