Satellite Aerial Terrestrial Hybrid NOMA Scheme in 6G Networks: An Unsupervised Learning Approach

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***Abstract*—Hybrid satellite aerial terrestrial networks (HSATNs) are a promising solution towards tackling coverage and mobility issues in sixth generation (6G) networks. This paper presents a novel transmission scheme in the context of HSATNs, which allows pairs of terrestrial users to be simultaneously served via the satellite and the aerial base station (ABS). To this aim, non-orthogonal multiple access (NOMA) technique is adopted, at the ABS, by applying a rule-based hybrid NOMA and orthogonal multiple access (OMA) schemes. Comparisons between a standalone NOMA-based satellite transmission and the proposed method, reveal that significant sum-rate gains can be harvested under varying system parameters.**

***Index Terms*—6G, Hybrid NOMA/OMA, Machine Learning, Satellite, UAV.**

I. Introduction

The sixth generation (6G) network has already been commenced as a new research initiative, following on from the evolving 5G network. This new type of network envisions sophisticated device-to-device (D2D) and machine-to-machine (M2M) communications [1], innovative artificial intelligence (AI) techniques, Internet of Everything (IoE) applications connecting people, data, things through processes [2]. Interoperability and convergence between terrestrial and satellite infrastructures will be a prerequisite in the 6G networking. Also, the new space era of non-terrestrial networks (NTNs) comprising of aerial networks, low Earth orbit (LEO) and especially very low Earth orbit (VLEO) satellites has emerged, enabling the path to 6G evolution [3], [4].

Hybrid satellite-terrestrial networks (HSTNs) have been proposed as an efficient approach towards improving spectral efficiency and increasing the users' reliability all over the world [5], [6]. The available spectrum resources of these networks can be further exploited by adopting the non-orthogonal multiple access (NOMA) principle [7]–[9]. However, in the absence of line-of-sight (LoS) conditions, the performance of satellite communication systems is severely deteriorating [10].

In the context of HSTNs, the unmanned aerial vehicle (UAV)-based communications are expected to improve the performance in various ways. In general, the UAV-aided NOMA schemes have gained the interest of the academia and the industry for various applications in the beyond 5G networks [10]–[13]. Focusing on the scenario where the UAVs are adopted in satellite terrestrial communication networks, they could be employed in the NOMA scheme as an intermediate node for increasing the possibility of obtaining LoS conditions [10], [13].

All-in-all, and to the best of our knowledge, no studies can be found related to the intelligent integration of aerial and satellite segments in 6G networks by utilizing a hybrid NOMA and orthogonal multiple access (OMA) transmission schemes. Motivated by this observation, in this paper, we propose a novel satellite aerial terrestrial cooperative network scheme, which will be termed SATCON. More specifically, SATCON is formed with the integration of aerial base station (ABS) in the existing satellite network by efficiently combining two unsupervised machine learning (ML) algorithms, namely k-means and k-medoids. Furthermore, the proposed system promotes efficient cooperation between ABS and satellite through an innovative hybrid NOMA/OMA approach, avoiding the waste of resources and energy. Compared to standalone satellite NOMA transmission with optimal user pairing [14], namely SAT-NOMA, SATCON increases the sum rate and, at the same time, provides higher spectral efficiency for varying satellite channel conditions and ABS bandwidth.

II. System Model

A. Topology

A network consisting of a VLEO satellite as part of a VLEO satellite constellation, an ABS, and $N = 2K$ mobile terminals (MTs), uniformly distributed within the ABS coverage area W is considered, as depicted in Fig. 1. Furthermore, the ABS and the MTs are within the coverage area of the VLEO satellite. Each MT_i $(1 \leq i \leq N)$ has coordinates $U = \{u_1, u_2, ..., u_N\} \in W$, where $u_i = (x_i^u, y_i^u, z_i^u)$. The MTs receive their data directly via the satellite link and through the decode and forward (DF) ABS relay, via the air to ground (A2G) link. The satellite is equipped with an antenna with

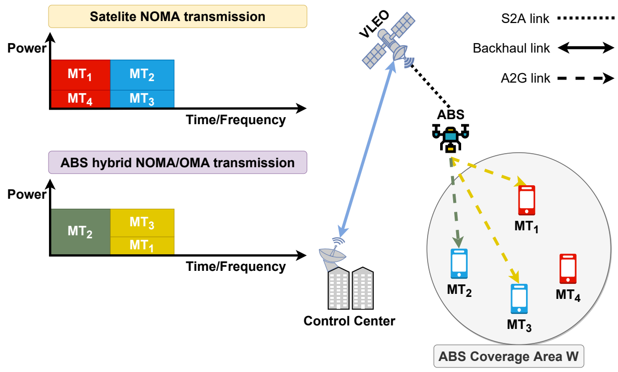

Fig. 1: System model for $K = 2$ pairs of MTs and $N = 4$ MTs in total.

transmit gain G_t^s, and total available transmit power P_s. Also, the satellite downlink operates at a frequency f_s, and the total available bandwidth is B_s. Furthermore, the ABS is equipped with two antennas, one for the reception of the satellite signals via the satellite to air (S2A) link (with an antenna gain denoted as G_r^{sd}) and one for re-transmitting the satellite signals to the MTs via the A2G link (with a gain G_t^d). The operating frequency of the A2G links, i.e., between ABS and MTs, is $f_d \neq f_s$, and the total available bandwidth is B_d. Each MT_i has two antennas, one for the reception of the satellite signal with gain G_r^s and another for the reception of the ABS signal with gain G_r^d. The A2G and satellite signals are received by the MTs simultaneously.

From the system point of view, we consider a zero touch commissioning (ZTC) cloud radio access network (C-RAN) model consisting of a control element that performs automated resource discovery and manages the ZTC procedures in the cloud control center, such as the instantiation, configuration, and synchronization of SATCON. Finally, the formed on-demand 6G network consists of ultra-reliable low latency communication (URLLC) and enhanced mobile broadband (eMBB) network slices responsible for routing the control and data plane information, respectively [15].

B. Channel model

The fading environment for the land mobile satellite (LMS) channel is described through the Loo's model distribution, where the power of the LoS component is log-normally distributed with parameters (α, ψ), while the power of the multipath component (MP) follows the Rayleigh distribution with the channel complex coefficient being represented by h_i^s for each MT_i assuming zero mean and variance $\sigma_s = \sqrt{0.5 \cdot 10^{\frac{MP}{10}}} \sim \mathcal{N}\left(0, \sigma_s^2\right)$. Also, path loss attenuation using the free space path loss (FSL) model is considered being denoted as L_i^{FS} for each MT_i. In addition, a maximum Doppler shift of 40 kHz is assumed and modeled with the Jakes model.

Regarding the A2G link between the ABS and the MTs, the multipath fading is modeled by the Rayleigh distribution with zero mean and unit variance $\sim \mathcal{N}(0, 1)$. The channel complex coefficient is h_i^d for each MT_i. Also, path loss attenuation of the ABS's signal is modeled using the elevation angle-based path loss model [16], in an urban environment, and it is expressed as follows:

$$L_i^{A2G}(h, r_i) = 20 \log \left(\frac{4\pi y_i f_d}{c} \right) + \eta_{LoS} P_{LoS}(h, r_i) + \eta_{NLoS} \left(1 - P_{LoS}(h, r_i)\right), \tag{1}$$

where h is the altitude of the ABS, r_i is the 2D Euclidean distance between ABS and MT_i, $y_i = \sqrt{r_i^2 + h^2}$ is the direct link that connects the ABS and the MT_i, and c is the speed of light. Moreover, P_{LoS} denotes the LoS probability between the ABS and MT_i and η_{LoS}, η_{NLoS} are the coefficients describing the propagation environment. In addition, concerning the S2A channel between the satellite and the ABS, the path loss attenuation is modeled using the FSL model and it is denoted as L_{sd}^{FS}.

Furthermore, the LMS, A2G, and S2A links are degraded by additive white Gaussian noise (AWGN). The noise power is calculated as the product of the Boltzmann constant κ, the receiver system temperature T_g, where $g = \{s, d\}$ and the available bandwidth B_g. Thus, the noise power of the satellite and aerial receiver at each MT is equal to $N_s = \kappa T_s B_s$ and $N_d = \kappa T_d B_d$, respectively. Additionally, the noise power of the satellite receiver at ABS is $N_{sd} = \kappa T_{sd} B_s$

III. SATCON

A. ABS placement process

For the intelligent integration of the ABS into the existing satellite network, the combination of the k-means and k-medoids unsupervised ML methods is utilized [17]. The two algorithms aim to find the point $p \in W$ where $p = (x_1^p, y_1^p, z_1^p)$ so that the sum of the distances of the users from this point is minimized. The total within-cluster dissimilarity of the k-means c and k-medoids m algorithms is $A_q = \sum_{u_i \in U} \|u_i - p_q\|^2$, where $q = \{c, m\}$. The objective of these two methods is to determine the point p_q that minimizes A_q and it can be expressed as follows:

$$\underset{p_q \in W}{\arg\min} \sum_{u_i \in U} \|u_i - p_q\|^2. \tag{2}$$

From the two suggested points, p_c and p_m, given from k-means and k-medoids, respectively, if $A_c < A_m$ then $p = p_c$, otherwise $p = p_m$. Due to the nature of these two ML methods to create groups through the input data, i.e., the coordinates of the users U, the initial height of the ABS will be the same as the average height of the users. Therefore, to obtain the optimal altitude at which ABS provides the best quality of service (QoS) to the MTs, first, we should identify the farther MT_i from the point p, where ABS is placed. Thereinafter, we should determine the height of the ABS h where pathloss with the MT_i is minimized through solving $\frac{\partial L_i^{A2G}(h, r_i)}{\partial h} = 0$.

B. Satellite NOMA transmission

For the satellite transmission, each MT_l $(1 \leq l \leq N)$ periodically reports the channel state information (CSI) of the LMS channel to the satellite that receives the complex channel coefficient h_l^s and calculates the channel gain including additional gains, losses, and the noise power of the satellite receiver N_s as:

$$\Gamma_l^s = \frac{G_t^s G_r^s}{L_l^{FS} N_s} |h_l^s|^2. \tag{3}$$

The satellite aims to create K pairs of MTs, where each pair will share the same sub-channel in the power and time domain, assigning different power allocation factors of the total satellite power P_s to each MT belonging to a pair. Towards this end, a NOMA optimal user pairing policy is adopted [14], where the satellite sorts the MTs in ascending order by the channel gain $\Gamma_1^s \leq \Gamma_2^s \leq \ldots \leq \Gamma_{2K}^s$ and matches the user MT_k with the user MT_{2K-k+1}, for $1 \leq k \leq K$. Hence, each pair consists of the strong satellite channel user MT_j^s, and the weak satellite channel user MT_i^s, with channel gains $\Gamma_j^s \geq \Gamma_i^s$, respectively.

The optimal power allocation factor β_j^s of MT_j^s can be calculated by the following expression:

$$\beta_j^s = \frac{\sqrt{1 + \Gamma_i^s P_s} - 1}{\Gamma_i^s P_s}. \tag{4}$$

According to the principle of NOMA, MT_i^s will immediately decode its own signal by the received satellite signal, while MT_j^s should first estimate the signal of the MT_i^s and then perform successive interference cancellation (SIC) to retrieve its own signal. The achievable rates of MT_j^s and MT_i^s are:

$$R_j^s = \frac{B_s}{K} \log_2 \left(1 + \beta_j^s P_s \Gamma_j^s\right), \tag{5}$$

$$R_i^s = \frac{B_s}{K} \log_2 \left(1 + \frac{\left(1 - \beta_j^s\right) P_s \Gamma_i^s}{\beta_j^s P_s \Gamma_i^s + 1}\right). \tag{6}$$

C. ABS hybrid NOMA/OMA transmission

As described previously, ABS is integrated into the satellite network to improve the QoS of terrestrial users. Towards this end, the ABS should first receive and decode the NOMA superimposed signals of each pair of MTs via the S2A channel. The S2A channel gain can be expressed as:

$$\Lambda_{sd} = \frac{G_t^s G_r^{sd}}{L_{sd}^{FS} N_{sd}}. \tag{7}$$

The maximum achievable decoding rates which succeed by the ABS through the S2A channel for each MT_j^s and MT_i^s in pair are:

$$R_j^{sd} = \frac{B_s}{K} \log_2 \left(1 + \beta_j^s P_s \Lambda_{sd}\right), \tag{8}$$

$$R_i^{sd} = \frac{B_s}{K} \log_2 \left(1 + \frac{\left(1 - \beta_j^s\right) P_s \Lambda_{sd}}{\beta_j^s P_s \Lambda_{sd} + 1}\right). \tag{9}$$

Note that, the ABS obtains all the pair indices from the VLEO through a dedicated control channel to identify the users comprising each pair and their role, e.g., strong or weak satellite channel users. Also, the ABS acquires the achievable rate R_l^s of each MT_l with the satellite, through the same channel.

Next, the ABS should forward the decoded signals to the MTs through the A2G channel, utilizing the proposed hybrid NOMA/OMA transmission scheme. Consequently, we consider that each MT_l reports the CSI of the corresponding A2G link to the ABS. Therefore, the ABS calculates the channel gain of the A2G link for each MT_l as follows:

$$\Gamma_l^d = \frac{G_t^d G_r^d}{L_l^{A2G}\left(h, r_l\right) N_d} |h_l^d|^2. \tag{10}$$

Following the same NOMA user pairing policy as the VLEO, the ABS forms K MT pairs, considering now the channel gains of the A2G links. Therefore, each pair consists of the strong A2G channel user MT_j^d, and the weak A2G channel user MT_i^d, where $\Gamma_j^d \geq \Gamma_i^d$. Subsequently, calculates the optimal power allocation factor β_j^d for the MT_j^d by replacing s with d in expression (4). Also, the achievable rates in NOMA, R_j^d and R_i^d, of the MT_j^d and MT_i^d, are given by the expressions (5) and (6), respectively, by replacing again s with d. The rates that ABS can offer to MT_j^d and MT_i^d, utilizing the NOMA technique, are $R_j^{dn} = \min\left(R_j^d, R_j^{sd}\right)$ and $R_i^{dn} = \min\left(R_i^d, R_i^{sd}\right)$, respectively.

Lastly, the ABS has to decide whether it is profitable for each pair of MTs to transmit the superimposed signal or to transmit only the signal of one MT of each pair utilizing the OMA technique. Also, the ABS can avoid forwarding the satellite signals if the ABS transmission is not profitable for both MTs in pair. Therefore, the achievable rate that each MT_l can achieve from the ABS through OMA, is equal to:

$$R_l^o = \frac{B_d}{K} \log_2 \left(1 + P_d \Gamma_l^d\right). \tag{11}$$

Each MT_l will experience higher rates if the ABS uses OMA, i.e., $R_l^o \geq R_l^d$, since the same bandwidth as NOMA is allocated for OMA transmission, and whole P_d is allocated to MT_l. However, the maximum achievable OMA rate of MT_l is restricted by the expression $R_l^{do} = \min\left(R_l^o, R_l^{sd}\right)$, since the ABS may provide a higher rate to the MT_l, but the rate at which ABS decoded its signal from the VLEO is lower and vice versa. There are four different cases that the ABS considers for each MT pair:

1) **if** $R_i^s < R_i^{dn}$ **and** $R_j^s < R_j^{dn}$: In this case, the pair of MTs formed by the ABS profits from the NOMA transmission as both MTs achieve greater rates if served from the ABS instead of the satellite.
2) **if** $R_i^s < R_i^{dn}$ **and** $R_j^s \geq R_j^{dn}$: In this case, only MT_i^d profits from the ABS transmission. Thus, the ABS utilizes OMA and transmits only to MT_i^d for the time-slot allocated to this pair. MT_i^d achieves a rate equal to R_i^{do}.
3) **if** $R_i^s \geq R_i^{dn}$ **and** $R_j^s < R_j^{dn}$: In this case, only MT_j^d profits from the ABS transmission. Therefore, the ABS utilizes OMA and transmits only to MT_j^d for the time-slot allocated to this pair. MT_j^d achieves a rate equal to R_j^{do}.
4) Otherwise, the communication for this MT pair is not profitable and ABS does not transmit to these pair of users in order to save resources.

TABLE I: Simulation Parameters

Simulated frames	100,000
Number of MTs N	32
Satellite downlink frequency f_s	1.625 GHz
ABS downlink frequency f_d	2 GHz
Satellite transmit SNR	0 - 30 dB
System receiver noise temperature T_s	25.7 dBK
ABS transmit power P_d	30 dBm
System receiver noise temperature T_d	24.6 dBK
Satellite Tx antenna gain G_t^s	24 dBi
ABS Tx/Rx antenna gain (G_t^d and G_r^{sd})	9 dBi
MT Rx antenna gain G_r^g with $g = \{s, d\}$	0 dBi
Satellite Bandwidth B_s	5MHz

D. Toy Network

To better highlight the proposed method, let us focus on the considered network with $N = 4$ MTs, as depicted in Fig. 1. Concerning the satellite transmission, VLEO forms $K = 2$ pairs of users utilizing the NOMA optimal user pairing policy, $\{MT_1, MT_4\}$ and $\{MT_2, MT_3\}$, since $\Gamma_1^s \leq \Gamma_2^s \leq \Gamma_3^s \leq \Gamma_4^s$. Afterward, the satellite transmits the corresponding superimposed signals to each pair of MTs employing the NOMA optimal power allocation (see Fig. 1, upper left corner). Concomitantly, for the ABS transmission, we consider that $\Gamma_3^d \leq \Gamma_2^d \leq \Gamma_4^d \leq \Gamma_1^d$. Thus, the ABS forms the user pairs, $\{MT_1, MT_3\}$ and $\{MT_2, MT_4\}$, following the NOMA optimal user pairing and power allocation policy. Meanwhile, the ABS is within the coverage area of VLEO and thus receives and decodes the MTs' signals. Subsequently, the ABS utilizes the proposed hybrid NOMA/OMA rule-based method. For this network instance, the pair of users $\{MT_1, MT_3\}$ formed by the ABS profits from the ABS NOMA transmission, and thus the first condition of the proposed method is activated. In contrast, for the second pair of users formed by the ABS, $\{MT_2, MT_4\}$, only MT_2 profits from the ABS transmission. Therefore, following the second condition of the rule-based method, the ABS utilizes OMA and transmits only to MT_2 for the time-slot allocated to this pair (see Fig. 1, bottom left corner). Concerning MT_4, it is served through the VLEO.

IV. Performance Evaluation

In this section, the performance of the SATCON scheme is evaluated through a custom-made Matlab® simulator in terms of sum rate and spectral efficiency for different system parameters and transmission techniques. To conduct a more realistic simulation, we used the simplified general perturbations four (SGP4) model for simulating the satellite orbit. Furthermore, from CelesTrak [18], we obtained the two-line element set (TLE) file that contains the orbital parameters of the STARLINK constellation satellites. For the needs of the simulation, we used the satellite of the constellation STARLINK-3080. Also, we have considered a circular area of interest with radius $R = 500m$ in the capital of Greece, i.e., Athens, in a high dense urban region. The terrestrial MTs are generated randomly following the uniform distribution into this area. Also, we have considered the time intervals where the STARLINK-3080 satellite provides coverage to MTs with elevation angles $E = \{10°, 20°, 40°\}$.

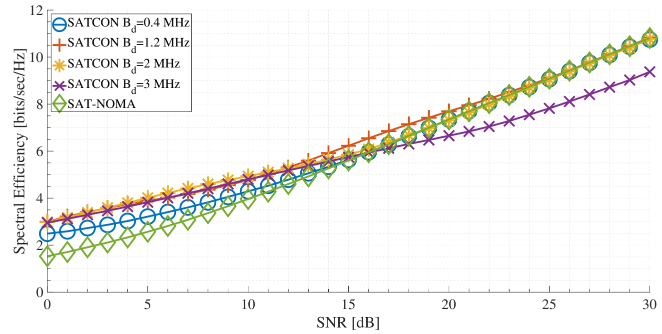

Fig. 2: Average spectral efficiency of MTs, for $E = 10°$ and different ABS bandwidth values $B_d = \{0.4, 1.2, 2, 3\}$ MHz.

Regarding the LMS channel, the Loo's model channel parameters (α, ψ, MP) are selected based on the values presented in Table 2 of [5], for an urban area, operating in the L-Band, where MTs are equipped with handheld antennas. Moreover, for the satellite-terrestrial channel, we define the cases of the weak channel (WC) MTs experiencing deep shadowing and strong channel (SC) MTs, representing the LoS situation. We set a dedicated scenario for the performance evaluation of SATCON scheme, where 50% of MTs are experiencing SC conditions, and the other 50% are in deep shadowing, i.e., WC conditions. Finally, Table I describes the key parameters of the simulation setup.

In Fig. 2, a comparison between the SATCON and the SAT-NOMA transmission schemes is presented, in terms of spectral efficiency for $E = 10°$ and different ABS bandwidth values B_d. For satellite transmit SNR in range 0 to 11 dB, it can be observed that SATCON with $B_d = 2$ MHz outperforms SAT-NOMA and any other configurations regarding the value of B_d. However, for transmit SNR in the range 11 to 26 dB, the proposed technique with $B_d = 1.2$ MHz achieves better results than any other value of B_d compared to SAT-NOMA scheme. For SNR values greater than 26 dB, SATCON with $B_d = 1.2$ MHz achieves slightly better results than the compared scheme with almost identical performance. Also, we can observe that SATCON with $B_d = \{0.4, 1.2, 2\}$ MHz outperforms the compared technique, especially in low transmit SNR values. Moreover, the proposed scheme with $B_d = 3$ MHz achieves better results in low to medium transmit SNR values, but SAT-NOMA surpasses SATCON with this configuration for medium to high SNR values. Therefore, there is an upper bound for the B_d that should not be exceeded to avoid wasting resources.

In Fig. 3, the sum rate performance between the proposed and the compared transmission schemes is examined, for $E = 10°$ and different ABS bandwidth values B_d. It can be observed that SATCON with $B_d = \{2, 3\}$ MHz outperforms the SAT-NOMA technique for all satellite transmit SNR values. SATCON with $B_d = 1.2$ MHz provides greater sum rate as compared to SAT-NOMA for SNR in range 0 to 27 dB. For SNR values greater than 27 dB, SATCON and SAT-NOMA have identical performance in terms of sum rate since the transmission from the ABS is not beneficial for the

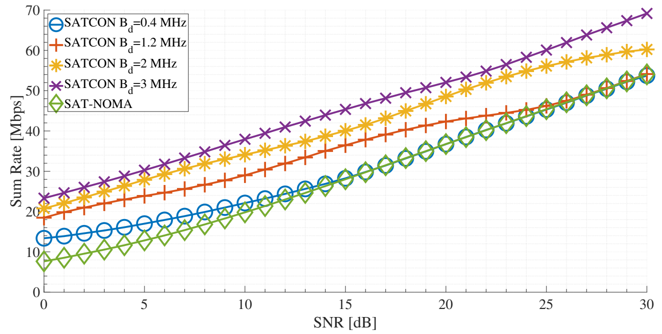

Fig. 3: Sum rate for $E = 10^{\circ}$ and different ABS bandwidth values $B_d = \{0.4, 1.2, 2, 3\}$ MHz.

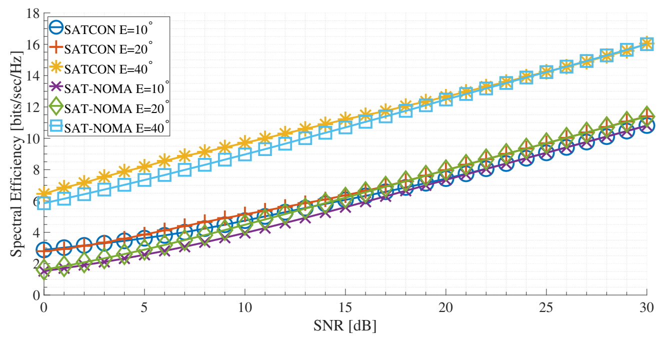

Fig. 4: Average spectral efficiency of MTs, for $B_d = 1.2$ MHz and for different satellite elevation angles $E = \{10^{\circ}, 20^{\circ}, 40^{\circ}\}$.

terrestrial users. Also, the proposed scheme with $B_d = 0.4$ surpasses the compared scheme at low to medium SNR values, and for medium to high SNR values, the difference between the sum rate of the two schemes is negligible. Moreover, for SATCON, we observe that the larger the ABS bandwidth used, the greater the sum rate. Nevertheless, the findings from Figs. 2 and 3 conclude that SATCON with large values of B_d could achieve superior performance against a standalone NOMA satellite transmission scheme but at the expense of worst spectral efficiency for medium to high SNR values.

Fig. 4, illustrates the spectral efficiency performance of SATCON and SAT-NOMA schemes, for $B_d = 1.2$ MHz and for different satellite elevation angles $E = \{10^{\circ}, 20^{\circ}, 40^{\circ}\}$. Comparing the two schemes' performance for the same elevation angle, the proposed one exhibits the best performance up to SNR 25 dB. The two schemes provide almost identical performance for SNR values greater than 25 dB. Quite interesting is that for low to medium transmit SNR values, SATCON for $E = 10^{\circ}$ outperforms SAT-NOMA for $E = 20^{\circ}$.

V. Conclusions and Future Directions

This paper proposed a cooperative transmission scheme between a satellite and an ABS, namely SATCON, to serve terrestrial users in the context of 6G HSATNs, and its operation was presented in detail. Comparisons with a NOMA-based satellite transmission scheme outlined the gains of SATCON in terms of spectral efficiency and system sum rate for different system parameters and various channel conditions. As future work, we consider to form a cost function to identify the optimal ABS bandwidth value that achieves the maximum sum rate and at the same time the maximum spectral efficiency.

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