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The Application of Power-Domain Non-Orthogonal Multiple Access in Satellite Communication Networks

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ABSTRACT Satellite communication networks are expected to be indispensable as part of an integrated complement for the upcoming 5G networks since they can provide the most comprehensive coverage and reliable connection for areas where are economically unviable and/or difficult to deploy terrestrial infrastructures. Meanwhile, the power-domain non-orthogonal multiple access (NOMA), which can serve multiple users simultaneously within the same time/frequency block, has been viewed as another promising strategy used in the 5G network to provide high spectral efficiency and resource utilization. In this paper, we introduce a general overview of the application of the NOMA to various satellite architectures for the benefits of meeting the availability, coverage, and efficiency requirements targeted by the 5G. The fundamental and ubiquitous features of satellite link budget are first reviewed. Then, the advantage and benefit of introducing the NOMA scheme in various satellite architectures, such as conventional downlink/uplink satellite networks, cognitive satellite terrestrial networks, and cooperative satellite networks with satellite/terrestrial relays, are provided, along with the motivation and research methodology for each scenario. Finally, this paper reviews the potential directions for future research.

INDEX TERMS Power-domain non-orthogonal multiple access, satellite networks, cognitive satellite terrestrial networks, cooperative satellite terrestrial networks, 5G.

I. INTRODUCTION

Satellite communication networks have received considerable attention from research and industry, for their ability to provide radio access for areas where terrestrial wired/wireless infrastructures are uneconomical and/or difficult to deploy [1]. Thanks to its ubiquitous superiority in offering higher quality of service (QoS) at a relative low price for users, satellite networks can also offer a remarkable increase in the types of both fixed and mobile satellite services. As a potential component in the fifth generation (5G) ecosystem, satellite networks have been viewed as a promising technology for smart grid, Internet-of-Thing (IoT), wireless sensor networks (WSN), space-based cloud, vehicular ad-hoc networks, and massive machine type communications (mMTC) for the upcoming 5G era [2]. Under such circumstances, to guarantee global service, support innovative 5G scenarios, and reduce operational costs, future satellite networks are expected to be integrated, hybrid, and heterogeneous, which can be widely deployed and extended using different platforms on geostationary orbit (GEO) satellites and non-geostationary orbit (NGSO) satellites (i.e., medium/low earth orbit (M/LEO) satellites), along with emerging key techniques, such as multi-satellite/terrestrial relay, cooperative transmission, and cognitive radio (CR), to provide satisfactory services for the growing number of terminals within limited spectrum.

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TABLE 1. Multiple access schemes used in current satellite networks.

Category	Scheme	Key characteristics	Drawback
Fixed assignment	FDMA TDMA CDMA	• Users are served with different frequency/time/code blocks	• Inefficient resource utilization • Limited users can be served
Random assignment	ALOHA	• Terminal send its data at any time • The transmission time and the processing can be minimized	• Data collision when multiple users are deployed • No guarantee in QoS
Demand assignment	DAMA	• Dynamically allocate resource according to users' requests • Resource reservation is needed	• Extra time required for an explicit reservation • Time slots need to be captured for an implicit reservation

Until now, satellite systems mainly adopt orthogonal multiple access (OMA) scheme to provide service [3]. For example, beamforming technique combined with the use of precoding at the gateway/satellite can divide a satellite footprint into beams and also realize the space division multiple access (SDMA). Then, as shown in Table 1, frequency-division multiple access (FDMA), time-division multiple access (TDMA), or code-division multiple access (CDMA) are adopted to provide services in fixed channel allocation protocols, while ALOHA and demand assignment multiple access (DAMA) schemes are used in a random assignment and a demand assignment, respectively. Despite that the application of FDMA/TDMA/CDMA schemes can effectively avoid intra-beam interference and simplify the signal detection, the fact that a single orthogonal resource block only can serve one user restricts further improvement on the spectrum efficiency and capacity for satellite networks. Moreover, the use of ALOHA can cause data collisions in the case of high numbers of terminals while DAMA requires resource reservation. Suffering from low spectrum utilization efficiency and limited number of users, OMA schemes cannot provide an enhanced performance at high resource efficiency to meet the explosive growth of traffic demand for future satellite networks. Therefore, new multiple access schemes, which can harmoniously integrate with OMA techniques in existing satellite architectures, should be taken into account, which is the main motivation and focus of this article.

Recently, a novel multiple access scheme, referred to as power-domain non-orthogonal multiple access, which is abbreviated as NOMA in this paper, has been proposed as a promising multiple access principle. The key idea of this scheme is to superpose multiple signals in the power domain at the transmitter and use successive interference cancellation (SIC) at the receiver[1], and thus, the NOMA scheme can serve multiple users simultaneously on the same time/frequency block and provides an improved spectral efficiency at the cost of reasonable increased complexity [6]. Moreover, this scheme can integrate with existing OMA schemes since power domain is explored to perform multiple access [7]. For these advantages, the NOMA scheme has been viewed as one of the most promising strategies for meeting the 5G requirements and has received a great deal of attention from academic researchers and industry. Until now, numerous studies on the performance of NOMA in cellular networks have been conducted and proven that system performance with the NOMA scheme is superior to those with conventional OMA schemes [8], [9]. Moreover, the advantage of the NOMA scheme is increased if the difference in channel gains is enlarged. In view of these benefits, this article aims to provide a comprehensive overview of potential and applicable NOMA schemes in various satellite architectures, especially for the unified frameworks with 5G infrastructures.

The main contribution of this paper are as follow: Firstly, a generalized framework for the characteristics of satellite transponder model and channel model is presented, and the feasibility of applying the NOMA scheme in satellite networks is proven. Then, to provide reader a clear picture, existing studies in NOMA-based various satellite networks are carefully considered. Specially, the application of the basic and cognitive NOMA schemes in conventional satellite networks and cognitive/integrated satellite terrestrial networks are listed, the motivation and research methodology for each scenario are mentioned. Moreover, the benefit that can be achieved by introducing the cooperative NOMA scheme in cooperative satellite networks with satellite/terrestrial relays is also described. Finally, potential directions in the field of NOMA-based satellite networks are highlighted for future research.

The rest of this article is organized as follows. The fundamentals and ubiquitous features of satellite communication systems are presented in Section II. Possible applications of the basic NOMA scheme, cognitive NOMA, and cooperative NOMA schemes in various satellite networks are studied in Section III, together with essential and representative analysis

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[1] The SIC and power allocation strategies in the NOMA scheme are not the cases in [4] and [5], where transmitters send two copies of the same packet in two randomly selected slots within a RA frame, which is composed of multiple time slots, receiver uses the SIC strategy to clear up the collisions stemmed from replica bursts.

and simulations. Potential directions for future research are discussed in Section IV. Finally, we draw conclusions in Section V.

II. FUNDAMENTALS OF SATELLITE TRANSMISSION

Compared to terrestrial networks, in which the power allocation strategy is executed directly at a base station (BS), satellite networks are more complicated in the processing of data traffic. Thus, before incorporating various NOMA schemes in satellite networks, the characteristics of satellite transponder model and channel model are first introduced.

A. SATELLITE TRANSPONDER MODEL

In satellite communication systems, two types of repeaters are used, namely, transparent and regenerative repeaters [2]. A transparent (bent-pipe repeater) satellite, such as the IRIDIUM system, only amplifies and forwards the received signal and acts as an amplify-and-forward (AF) relay node. While a regenerative satellite, i.e., the SPACEWAY system, can perform demodulation, baseband processing, and re-modulation with on-board processing. For different types of satellites, the power split strategy for the NOMA scheme can be performed at different locations, such as a gateway (GW) for a transparent satellite and on-board processing for a regenerative satellite. In this paper, for simplicity, we assume that the power splitting process is conducted on the satellite, whether or not it is practically conducted on the GW or the satellite.

B. CHANNEL MODELING

In satellite communication system, an entire link budget of satellite→User j ($j \in \{1, 2, \ldots, M\}$,), including propagation loss, beam gain, channel statistical property, and receive antenna gain, can be given by

$$Q_j = L_j G_j G_s(\varphi_j)\hat{h}_j^2, \tag{1}$$

where

- L_j: Propagation loss which is mainly caused by attenuation or free space loss. It is a function of distance d from the satellite to the User j, the light speed c, and the frequency f_c of the transmission.
- G_j: The received antenna gain at the User j.
- $G_s(\varphi_j)$: Received beam gain at the User j which is related to the angle between User j and the beam center with respect to the satellite φ_j and the maximum beam gain at the on-board boresight G^S_{max} [10].
- $\hat{h}_j$: The estimated channel coefficient of link satellite→User j can be given by $\hat{h}_j = h_j + e_j$ with h_j and e_j denoting the perfect channel coefficient and the estimated channel error caused by user mobility and/or path loss, respectively [11]. Without loss of generality, we assume that the channel power gain $|h_j|^2$ follows a Shadowed-Rice (SR) model [12], which is flexible to fit data and evaluate performance for satellite propagation environments by characterizing a wide range of elevation angle θ_j, and has been widely applied in various frequency bands such as the UHF-band, L-band, S-band, and Ka-band.

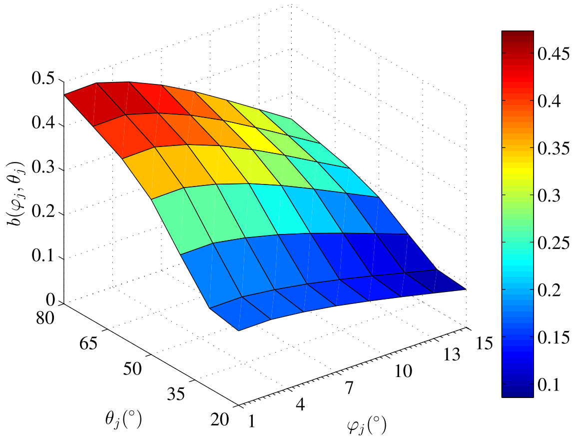

FIGURE 1. $b(\varphi_j, \theta_j)$ **achieved with different angle** φ_j **and elevation angle** θ_j**.**

By defining $b(\varphi_j, \theta_j) = Q_j/(L_j G_j G^S_{max})$, $b(\varphi_j, \theta_j)$ achieved with different angle φ_j and elevation angle θ_j is plotted in Fig. 1, from which we can find that the $b(\varphi_j, \theta_j)$ increases when either the angle φ_j decreases or the elevation angle θ_j increases. Note that different configurations of users, i.e., antenna sizes and gains, receiver qualities, and shadowing cause by users' mobility, can cause significant differences in channel gains, making the application of the NOMA scheme in satellite networks feasible and favorable. Thus, the benefit of the NOMA scheme can be exploited in various satellite architectures, such as satellite networks, cooperative and cognitive satellite terrestrial systems, which will be described in the next section.

III. APPLICATION SCENARIOS

In this section, the NOMA scheme and its variations are introduced in various satellite networks, including integrated/hybrid and heterogeneous architectures. Particularly, in all cases, only two users are paired to form a NOMA group because of twofolds: 1) Interference and additional complexity introduced at the receiver will be aggrandized greatly as the number of users admitted in one NOMA group is greater than two. 2) According to the result in [13], the number of users admitted in one NOMA group is limited by users' different demands, and the sum and ergodic rate were maximized when only two users are in a NOMA group. For convenience, user with good link condition is denoted as User p and the other one is denoted as User q in all cases.

A. THE APPLICATION OF BASIC NOMA SCHEME

As shown in Fig. 2, prior to the superposing coding operation, the transmitter will select users to be served via a scheduling strategy, such as random selection strategy. Then, in a downlink scenario, a linear superposition of multiple users' signals is broadcasted by allocating different power to each user. Indeed, the power is allocated based on users' feedback channel information and it is applied at each frame. On the

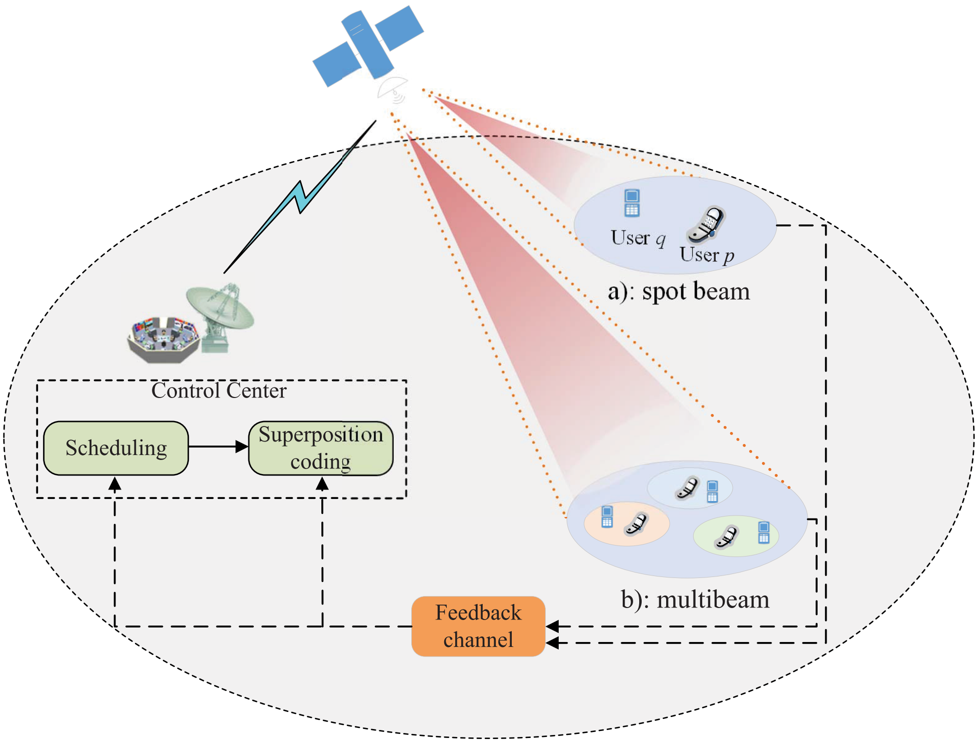

FIGURE 2. System model of NOMA-based conventional satellite networks: (a) spot beam and (b) multiple beams.

receiver side, different detection strategies are executed at different users. For example, User q, which may be closer to the edge of the beam and/or has lower antenna gain, is allocated with more transmission power to ensure that the intra interference caused by User p is relatively low and can decode itself information directly. While User p, although relatively experiences a better channel condition, must adopts the SIC strategy to decode its own information, since less power resource is allocated to it and its information is buried underneath.

In an uplink scenario, Users p and q simultaneously transmit to the satellite over the same time/radio block, with their maximum or controlled transmission power. Thus, with the NOMA scheme, a superposed signal is received at the satellite and the SIC strategy must be adopted to detect each user's signal. Opposite to the downlink environment, the signal of User p is decoded firstly and directly at the satellite, because its signal is stronger than that of User q. While the signal of User q must be decoded by applying the SIC strategy, which means that contribution from the signal of the User p has been already decoded and removed, the signal of User q still can be observed even if its channel condition is far worse than that of User p.

1) CONVENTIONAL SATELLITE NETWORKS

For the scenario depicted in Fig. 2(a), it can be either one or two beams isolated from several spot beams, adopting 4/7-frequency reuse such that cooperation among beams is nonessential or adopting full-frequency reuse strategy with one user in each spot beam. Since the first scenario is similar with a terrestrial cell, so that strategies on user pairing and power allocation in satellite networks can refer to those made in terrestrial networks, such as the larger difference in channel gains, the larger superiority of the NOMA scheme achieved. However, it is worth noting that the link characteristics of satellite networks are obviously different from those in terrestrial networks, i.e., non-negligible delay as well as path loss resulted from long distance and mobility from aeronautical or vehicular users all can cause significant errors on channel estimation, which will significantly degrade the estimation on users' channel state information (CSI) accuracy and further influence the user pairing processing. The achievable system capacity of two schemes with imperfect CSI is illustrated in Fig. 3, where the achieved rates of Users p and q with the NOMA scheme are $R_p^N = log(1+\alpha\gamma_p^T)$ and $R_q^N = log(1+(1-\alpha)\gamma_q^T/(\alpha\gamma_q^T+1))$, while that with the TDMA scheme are $R_p^T = 0.5log(1+\gamma_p^T)$ and $R_q^T = 0.5log(1+\gamma_q^T)$, where γ_p^T and γ_q^T are the SINR of Users p and q with the TDMA schemes, respectively, α is the split factor of transmission power P_s to User p, and N_0 denotes the variance of additive white Gaussian noise at users. As observed, the performance achieved with the NOMA scheme is superiority to that with the TDMA scheme.

As for the second scenario, if without beam cooperation, it is similar to the two-user interference channel. Thus, information intended to Users p or q can be divided into two parts,

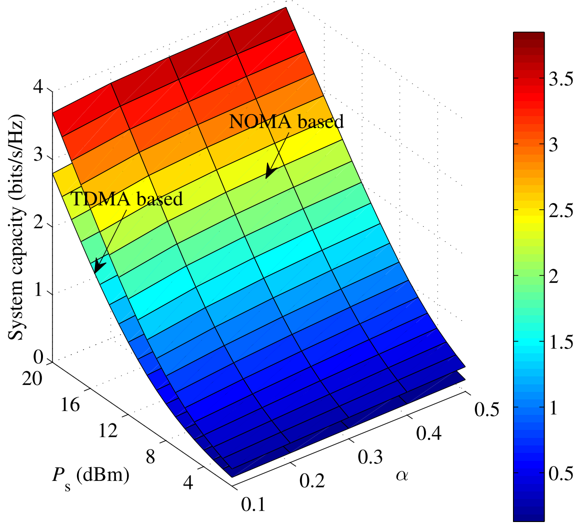

FIGURE 3. System capacity for two access schemes versus P_S and α, with the variance of estimated channel error being 0.5.

namely the common part, which can be decoded by these two users, and the private part, which only can be decoded by the intended user. To reduce the interbeam interference, Users p and q can jointly decode, regenerate, and cancel the common signals from their received signal and recover their corresponding private information. While with beam cooperation, the most suitable encode/decode strategy can be independently adopted within each pairing beams to improve the achievable rate regions.

For the scenario depicted in Fig. 2(b), multibeam satellite [14] is another scenario where the application of the NOMA scheme has been shown to be very beneficial [15], [16]. By serving users simultaneously in each spot beam with the same resource block, i.e., time/frequency/code resource and allocating different frequency/code resource to different beams in a cluster, the satellite system is overloaded at a relative low complexity since only two users in each spot beam is admitted to form a NOMA group. To serve this type of communications, existing works have shown that the introduction of the NOMA scheme can further provide an enhanced performance gain over the OMA scheme. However, two key challenges for this case are how to effectively group users and design the power allocation factor for each beam, especially with the increase of beam numbers.

2) COGNITIVE SATELLITE TERRESTRIAL NETWORKS

With the rapid growth in satellite traffic, the licensed spectral resources appear to be insufficient and the problem of spectrum scarcity is becoming more and more obvious, which motivates the use of cognitive radio (CR) technology and the emerging cognitive satellite terrestrial networks (CSTN) [17], [18]. Interestingly, we note that the motivation of applying the NOMA scheme is exactly the same as CR, i.e., increase the spectrum efficiency, but the solution provided by the NOMA scheme is to explore the power domain for multiple access. It is obvious that a further performance improvement can be observed if we integrate the NOMA scheme with CSTN. On the one hand, the use of the CR strategy can ensure spectrum sharing between a satellite network, termed as a primary/cognitive network, and a terrestrial network which acts as a cognitive/primary network, and thus, the spectrum utilization efficiency of the overall system will be increased. On the other hand, the introduction of the NOMA scheme in CSTN ensures multiple users, access and further improves spectrum utilization without extra resource consumption. However, in the CSTN, transmit power of cognitive network must be constrained so that the communication of primary user will not be deteriorated. Moreover, interference from the shared network cannot be neglected, which means that channels of NOMA users suffer interference not only from the intra-group but also from co-channel interference. For example, although the achievable rates of Users p and q still can be written as that given in the example of Conventional Satellite Networks, the effect of co-channel interference and limited transmit power must be taken into consideration in γ_p^T and γ_q^T. Thus, to serve this type networks, power allocation among NOMA users should be carefully designed to ensure user fairness. As shown in [19], incorporating the NOMA scheme with the CSTN can provide an enhanced spectrum utilization efficiency compared to OMA, if power allocation coefficients are reasonably designed.

B. THE APPLICATION OF COGNITIVE NOMA SCHEME

Although with the help of the NOMA scheme, high spectrum and energy utilization efficiencies of NOMA based satellite networks can be achieved, the QoS targets of users must also be taken into consideration to provide reliable services. In this regard, a variation of the NOMA scheme, referred to as cognitive NOMA scheme, has been proposed [20]. The key merit of this type scheme is to view some or all users in a NOMA group as the primary users, whose QoS requirements must be met in the power allocation processing.

1) CONVENTIONAL SATELLITE NETWORKS

By assuming that User q has a strict data rate requirement and it is a primary user, the power allocation coefficient α should satisfy $(1-\alpha)\gamma_q^T \geq \gamma_{thq}(\alpha\gamma_q^T+1)$, where γ_{thq} is the target SINR of User q. Then, the power allocated to User p can be obtained as $\alpha = \max\left\{\frac{\gamma_q^T-\gamma_{thq}}{\gamma_{thq}\gamma_q^T+\gamma_q^T}, 0\right\}$, which means that for a large SINR requirement γ_{thq}, no resource is allocated to User p since it is viewed as a secondary user. With the incorporation of the cognitive NOMA scheme, not only the QoS requirements of primary users can be guaranteed, but also an improved resource utilization efficiency can be achieved since additional user can be admitted to access when any power left afterwards.

Specially, to compare achievable data rates of cognitive NOMA and TDMA schemes, we set rates achieved with the TDMA schemes as the QoS targets for Users

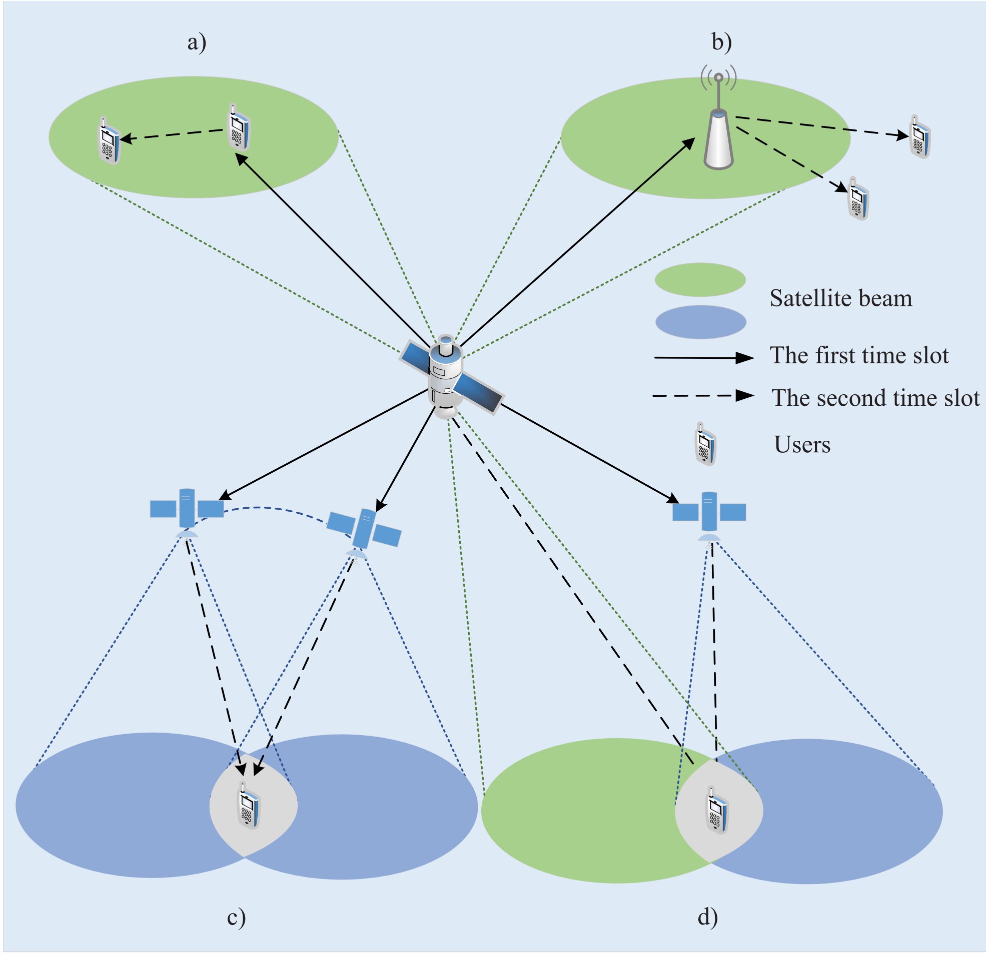

FIGURE 4. System model of cooperative NOMA-based satellite networks: a) cooperation among users, b) cooperation with a dedicated relay, c) cooperation with multi-satellite relays, and d) cooperation with a single satellite relay.

p and q, respectively. Then, when α falls in the area $\left(\frac{1}{\left(1+\gamma_p^T\right)^{0.5}+1}, \frac{1}{\left(1+\gamma_q^T\right)^{0.5}+1}\right)$, the larger power allocated to the user with good channel quality (User p), i.e., α increases, the better the performance of User p is [21]. At the same time, the performance of User q with the NOMA scheme is still better than that with the TDMA scheme. Then, we can draw a conclusion that with the cognitive NOMA scheme, both users' rates are superior to those with the TDMA schemes.

2) INTEGRATED SATELLITE TERRESTRIAL NETWORKS

Similarly to the CSTN, integrated satellite-terrestrial networks (ISTN) are also motivated by the fact that the utilization efficiency of spectrum resource is not sufficient, and it is required in some cases to use the same frequency band in satellite and terrestrial networks [22]. However, frequency reuse between satellite and terrestrial networks cannot always meet the rapid growing traffic requirement and user fairness. And thus, implementing the NOMA scheme in the ISTN is useful to support a further enhanced spectrum efficiency [23], [24]. Particularly, in the ISTN, satellite network is complementary to terrestrial networks to extend coverage and improve reliability, which means that applying the NOMA scheme in cellular networks is more beneficial than that in satellite networks. By setting rate achieved with the TDMA schemes as the QoS target for the far user, the work [23] have shown that a Max-Min user pairing scheme can achieve higher performance over a random algorithm. However, two key challenges, such as the co-channel interference caused by frequency reuse and signals from satellite and terrestrial transmitters in this heterogeneous networks, need to be carefully addressed for the interference management purpose to achieve a good performance.

C. THE APPLICATION OF COOPERATIVE NOMA SCHEME

In satellite communications, direct links between the satellite and terminals are sometimes deteriorated and even unavailable when terminals are deployed in masking effect areas or in spot beam edge. Under this condition, integrating the NOMA scheme with the relay technique can improve system performance in terms of reliability and capacity. As shown in Fig. 4, four types of cooperative NOMA based satellite networks are considered in this subsection and described as follows.

1) COOPERATION AMONG USERS

Under the circumstance of Fig. 4(a), User p can act as a DF relay node and forwards information for User q, since with the SIC strategy, the information of the user with bad channel quality is available at the user with good link condition [25]. Thus, by exploiting the prior information available in the NOMA scheme, the deployment of relay node is unnecessary, which is very economic and beneficially for areas with low-density populations and/or areas without grid power supply. Moreover, even when the link of satellite→User q is available, the system performance achieved with this type of cooperation NOMA scheme is still superior to that with the TDMA scheme [26]. This is because that although two time slots are needed in both NOMA and TDMA schemes, the reliability of User q can be further enhanced by cooperating among NOMA users.

2) COOPERATION WITH A DEDICATED RELAY

If the direct links of Users p and q are all unavailable, as shown in Fig. 4(b), a relay node with AF or DF protocol must be adopted to forward signals for users simultaneously. Since only two time slots are needed for multiple users to access in this type of cooperative NOMA scheme, while four time slots are needed for these two users with the TDMA scheme. In this regard, the waiting time for service and reliability of users can be reduced and improved, respectively [27]. Here, it is worth noting that if a AF relay protocol is adopted, the superposed information received at the relay node is firstly amplified with a fixed or a variable gain factor, and then forwarded to NOMA users. In this case, the achievable rates of Users p and q can be respectively given by $R_p^N = \log\left(1+\frac{\alpha\gamma_{sr}^T\gamma_{rp}^T}{\gamma_{sr}^T+\gamma_{rp}^T+1}\right)$ and $R_q^N = \log\left(1+\frac{(1-\alpha)\gamma_{sr}^T\gamma_{rq}^T}{\alpha\gamma_{sr}^T\gamma_{rq}^T+\gamma_{sr}^T+\gamma_{rq}^T+1}\right)$, where γ_{sr}^T, γ_{rp}^T, and γ_{rq}^T are the SINRs of links from the satellite→relay node, relay node→User p, and relay node→User q. While if the DF protocol is adopted, firstly, the relay node must decodes the information intended to Users p and q with the SIC strategy, and then split the transmission power at the relay node to superpose those two signals and transmit to users.

3) COOPERATION WITH MULTI-SATELLITE RELAYS

For the scenario considered in Fig. 4(c), the direct link between the source satellite and the ground user is unavailable, satellites which have lower earth orbits act as relays to forward information [28]. During the first phase, signals for two time slots are superposed and transmitted from the source node, relays decode their corresponding signals by using the SIC strategy. During the second phase, relays forward different slot signals to the ground user, and SIC is adopted to combine its received signals. It is worth note that the environment from the source node to relays is similar to that in the first case of Fig. 2(a), in which power split is processed at the transmitter side. While the environment from relays to the ground user is similar to that NOMA uplink scenario, where multiple signals from differed transmitter are received and SIC is applied at the receiver side.

4) COOPERATION WITH A SINGLE SATELLITE RELAY

If with a poor direct link quality, as shown in Fig. 4(d), a single satellite relay node can be applied to provide an enhance source utilization efficiency. In this scenario, similar to the second case of Fig. 2(a), the signal can be divided into two parts, i.e., source and relay parts. The relay part transmitted with the help of the relay node, while the source part is transmitted directly from the source satellite. At the ground user, signals from two different paths are combined and decoded by using the SIC scheme.

IV. FURTHER RESEARCH DIRECTIONS

Although system performance can be further improved by introducing the NOMA scheme in various satellite architectures, there still needs numerous efforts to fully unlock the advantage and potential of NOMA scheme in satellite networks. In this section, some of those discussions and potential research directions are presented.

A. NOMA BASED SATELLITE CACHING

Conventional satellite network suffers from inefficient use of the available bandwidth resources along with inevitable latency due to the long propagation. In an effort to address these drawbacks, a caching-enabled satellite system, in which caching technique is incorporated to enable the satellite nodes to store the frequently required contents and serve the users' requests conveniently, has been proposed as an effective method to improve the network performance in terms of QoS, delay, and throughput [29]. By introducing the NOMA scheme, the cache-aided satellite systems can not only significantly reduce the multiuser interference power, but also achieve a flexible decoding order, by performing the cache-aided interference cancellation before SIC processing. However, it is worth noting that the cache-aided NOMA in satellite networks may lead to challenges in cache placement and cache delivery designs. To address this problem, machine learning algorithms, i.e., reinforcement learning and neural networks, can be introduced to jointly design the cache placement and delivery.

B. NOMA BASED SATELLITE IoT

Satellite based Internet of Things (IoT) is proposed to ensure IoT devices, which are distributed over a large area with diverse service requirements, to access internet at any time/place within limited time/spectrum resource [30]. Under the requirements for large numbers of connectivity, the NOMA scheme should be considered in the satellite IoT network to further enhance the system performance in terms of user fairness, spectrum efficiency, and the lifetime of satellite solar panel or battery pack. Moreover, to coordinate heterogeneous users' access, a joint scheme considers priorities and rate requirements should be studied, which remains a challenging research topic.

C. NOMA BASED SATELLITE DATA OFFLOADING

To achieve coverage extension and massive connectivity, ultra-dense LEO networks are integrated with terrestrial networks to provide an alternative and efficient approach for data offloading [31]. To further exploit the benefits of the LEO constellation, we can see that the number of served users and resource utilization efficiency can be further enhanced by applying NOMA based traffic offloading. However, handover between LEO satellites, inter/intral-cell interference management, user scheduling, and power allocation within each NOMA group need to be further explored to push toward the application of NOMA scheme.

V. CONCLUSIONS

In this article, the foundation of introducing the NOMA scheme in satellite networks has first been presented. And then, the applications of the NOMA scheme in different architectures, including the conventional satellite networks, the cognitive satellite terrestrial networks, and the cooperative satellite terrestrial networks have been discussed, along with some performance analyses and/or simulation results. Finally, potential directions, i.e., performance boost with emerging techniques and applications in satellite communication systems, for future research works have also been discussed in the article.

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