MULTIPLE-USER TRANSMISSION IN SPACE INFORMATION NETWORKS: ARCHITECTURE AND KEY TECHNIQUES

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ABSTRACT

A SIN is a heterogeneous network that consists of various access nodes in different space mobile platforms, such as satellites, high altitude airships, and unmanned aerial vehicles. Due to their remarkable coverage performance, SINs play a key role in establishing a real-time and integrated communication framework for information acquisition and wideband signal transmission. This article presents the architecture of SINs and discusses three promising techniques for multiple-user transmission. Taking advantage of multiple-antenna systems, several transmission methods based on beamforming are investigated. We discuss various schemes for multiple-user access, with an emphasis on non-orthogonal approaches. Finally, cooperative transmission methods using different functional nodes are presented to enhance the performance of SINs.

INTRODUCTION

Recent years have witnessed an ever growing trend of exploiting space resources to build wireless network nodes, based on the concept of space information networking (SIN) proposed in 1998 [1]. There are various R&D activities worldwide in SIN development, including the space communication and navigation architecture by NASA and the Copernicus Programme by the European Commission. In general, a SIN consists of heterogeneous space-based network nodes (e.g., geostationary Earth orbit [GEO] satellites, medium Earth orbit [MEO] satellites, and/or low Earth orbit [LEO] satellites) and high altitude network nodes such as stratospheric airships/balloons and unmanned aerial vehicles (UAVs). SINs mainly provide real-time data acquisition, transmission, and processing services [2]. An example for real-time communication and data transmission is the Inmarsat communication system deployed in 1982 by the International Maritime Satellite Organization. A typical Inmarsat system, Inmarsat-4, has four GEO satellites that can cover most parts of the Earth. Later, in order to connect users anywhere and anytime, the Iridium communication system was launched, which consists of 66 LEO communication satellites [3].

The more and more fierce competition for satellite orbit resources has led to exploitation of the space in the stratosphere. For example, Google initiated Project Loon in 2013 [4]. This program aims to develop a communication network for remote areas through a number of helium balloons floating in the stratosphere, enabling billions of people to access the Internet freely. In order to serve a large number of users simultaneously, it is critical to have a well-designed SIN architecture supported by advanced techniques. Specifically, how to efficiently utilize the limited resources for communication and transmission poses significant technical challenges in a multiple-user scenario.

In this article, we mainly focus on the architecture of SINs, and investigate some key techniques for multiple-user transmission, as summarized in the following.

Multiple-Antenna Techniques: By exploiting the spacial degree of freedom, multiple antennas at transceivers can offer capacity improvement without demanding more radio spectral resources. As such, efficient transmission methods are discussed in the context of beamforming/precoding.

Multiple Access Techniques: To split the signals for different users without incurring interference, several existing multiple access approaches for SINs are reviewed. To improve radio spectral utilization efficiency, a novel non-orthogonal access scheme and its applications are introduced.

Cooperative Transmission Techniques: Taking advantage of the diversity provided by different functional network nodes, cooperative transmission methods are investigated, especially on the cooperation within a cluster and across different layers.

SINS: ARCHITECTURAL PERSPECTIVE

A typical architecture of SINs is illustrated in Fig. 1, which details the network nodes of a SIN such as communication satellites, stratospheric airships, and UAVs. As shown in Fig. 1, the SIN consists of two layers, that is, the space-based network layer and air-based (near-space-based) network layer. Each layer has a backbone network and an access network. The backbone network is responsible for resource management and access control, and consists of gateways and processing nodes that are connected to each other through laser links. Containing access nodes and users or the nodes in other layers, the access network enables multiple users or other network nodes to participate in the SIN by using microwave links. To enhance the performance of

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Digital Object Identifier:
10.1109/MWC.2019.1800274

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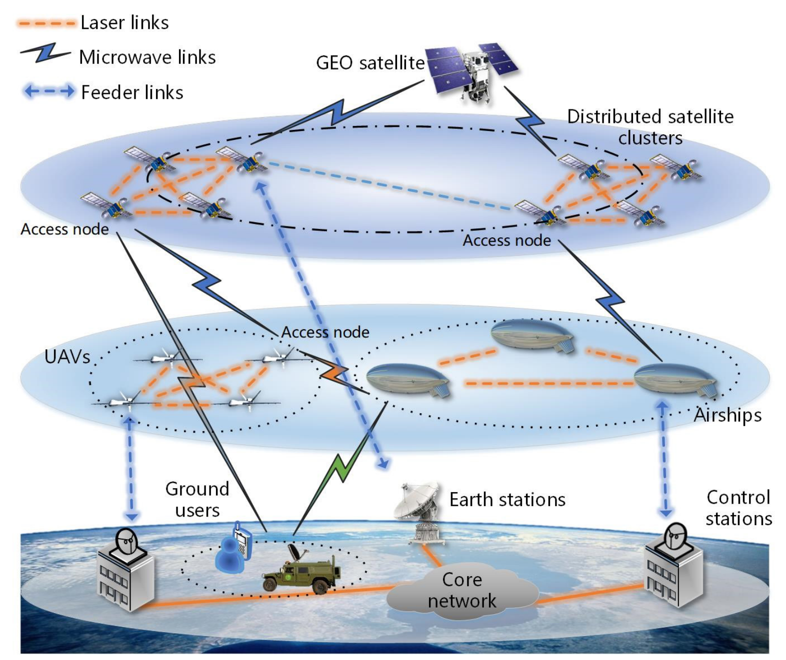

FIGURE 1. The architecture of a typical SIN.

a SIN, feeder links are always needed to transfer the data to Earth stations with strong processing ability. From the aspect of communication usage, any two users can be connected through one or more network nodes in a SIN. To expand the coverage range, the SIN enables messages to be exchanged between intra-layer or inter-layer nodes.

The space-based network mainly refers to the satellite-based network. Based on the altitude of different satellite orbits, the communication satellites can be briefly categorized into GEO and LEO satellites [3]. For the GEO satellites, the vertical distance between a satellite and the Earth equator is 35,786 km, which helps to keep them stationary relative to the Earth. In theory, three GEO communication satellites can cover most areas of the Earth, except the high latitude regions such as the poles. A representative application of the satellite communication system based on GEO satellites is Inmarsat. In an Inmarsat system, four GEO satellites are deployed over the Atlantic, Pacific, and Indian Oceans at the frequency bands of 1535~1542.5 MHz and 1636.5~1644 MHz. Another well-known GEO satellite application is the Thuraya system, which consists of three satellites. Similar to the Inmarsat system, the user link of Thuraya uses a frequency channel in 1626.5~1660.5 MHz and 1525.0~1559.0 MHz, while the feeder link occupies a frequency band in 6425.0~6725.0 MHz and 3400.0~3625.0 MHz. Practically, GEO satellite communication systems cannot provide mobile services for users in the northern and southern polar regions. As a result, LEO satellite-based communication systems have attracted lots of attention. As one of the earliest LEO satellite-based projects, the Iridium system started commercial applications in 1998. This system consists of 66 LEO satellites that are located separately on six orbits with an inclination of 86.4°. It is noteworthy that the inter-satellite link (ISL) technology that connects the nodes together allows the Iridium system to serve any users globally without deploying too many Earth stations [5]. Similarly, the user links in the Iridium system are allocated a frequency band of 1621.35~1626.5MHz, while the ISL adopts a Ka frequency band. Table 1 lists typical GEO/LEO satellite communication systems and their key techniques.

To overcome the limited orbital resources in satellite communication systems, near-space-based systems have emerged as a promising solution for SINs. In a near-space-based communication system, the network nodes can be airships, helium balloons, or UAVs. Compared to satellite communication, the most remarkable characteristics of stratosphere communication systems are the abundant spacial resources and easy airspace management. Encouraged by the ambition of supplying worldwide Internet connections, Google proposed the Project Loon program in 2013. In this plan, Google aims to launch thousands of helium balloons in the stratosphere to offer free Internet services. Using the balloons as relays, ground infrastructures can offer a data link up to 10 Mb/s to users in remote and rural areas. To facilitate easy access, 2.4/5.8 GHz frequency bands are selected to provide the services. In order to make the network work efficiently, four topologies are proposed [4], namely, spanning tree topology, hybrid topology, ring topology, and dual ring topology. For UAV-based systems, Aquila by Facebook and Titan by Google are under development to realize low-cost Internet and communication links. For example, Aquila will work on the E-band frequency spectrum and is expected to achieve a 20 Gb/s data rate service.

With different functional network nodes, development of an architecture of SINs can be summarized as follows: first building a space-based backbone network to guarantee worldwide coverage, then adding near-space-based backbone networks in hotspot areas through the access network in each layer, and integrating different layers to form a space-air-ground heterogeneous network with gateways. Specifically, each layer uses microwave links to deliver information.

Multiple-Antenna Techniques in SINs

The application of the multi-antenna technique, which is also known as multiple-input multiple-output (MIMO), is one of the most successful techniques incorporated in 4G terrestrial communication networks. MIMO techniques have been widely standardized in communication systems such as IEEE 802.20, 802.22, 802.11n, 802.16e, and 802.16m.

The rapid progress in terrestrial MIMO techniques motivates engineers to graft the strengths of multiple antennas onto satellites. Considering different orbits, the number of satellites, and the functions of satellite terminals, the MIMO infrastructure between satellites and terrestrial networks should be designed carefully based on service coverage, transmission delay, link geometry, channel impairments, special interference, and so on. In SINs, apart from the higher data rate request, it is expected that MIMO will perform as a flexible supportive technique for satellite communication networks to meet the demand of data distribution. Furthermore, multi-polarization MIMO is suitable for satellite and context-aware multi-user detection. Massive MIMO plays an important role in satellite multi-beam techniques and interference cancellation between multiple adjacent spot beams.

Satellite-Terrestrial MIMO Systems

The utilization of multi-beam satellites has increased dramatically to support high-speed data transmission with radio spectrum reuse [6]. Studies on incorporating MIMO with satellite communication systems result in the rapid development of multi-beam satellite systems. A typical single satellite-terrestrial multi-beam system is illustrated in Fig. 2, where the satellite acts as a relay to support a broad range of ground end-to-end communication. As can be seen from this figure, the satellite generates multiple beams based on a certain frequency reuse strategy. The ground terminals, assumed to be equipped with a single antenna, are randomly distributed over the area covered by multi-beam spots. In general, users in adjacent beams are allocated different frequencies. Thanks to the nature of multi-beams, a proper frequency reuse pattern can be determined for high spectral efficiency.

There are three kinds of multi-beam antennas: reflector multi-beam antenna, lens multi-beam antenna, and array multi-beam antenna. The reflector multi-beam antenna, including a single feed per beam and multiple feeds per beam, uses reflectors and complex beamforming to generate beams. The lens multi-beam antenna applies a lens to form beams. As a comparison, the array multi-beam antenna can easily utilize the benefits of terrestrial MIMO systems by exploring digital beamforming techniques, which are introduced in the next subsection.

Beamforming Techniques in SINs

Multiple-antenna beamforming is known as an efficient approach to realize multi-spot and multi-beam transmission. There are two objectives in satellite MIMO beamforming: achieving better capacity performance and mitigating interference (i.e., inter-beam interference), which are usually considered jointly to derive well-designed beamforming/precoding matrices. Other factors, such as antenna characteristics and user clustering strategies, should also be taken into account in multi-beam satellite communication engineering.

Digital beamforming, as one of the most promising beamforming techniques, has been widely studied and utilized in terrestrial communications. As stated in the previous subsection, digital beamforming techniques can be applied in satellite systems, which is regarded as a special case of array multi-beam antennas. In contrast to the directional (or phased array) antenna-based beamforming, the user groups are separated into virtual beams. Therefore, even if the same frequency is used for the entire user group, inter-beam interference can be mitigated by proper virtual beamforming (VBF) design, which results in higher spectral efficiency and capacity. Although the idea of VBF is inspired by terrestrial MIMO systems, there are several differences. On one hand, satellite channels usually include the line of sight (LoS) component with large path loss, which makes it difficult to utilize multi-user diversity due to limited channel dynamics. On the other hand, antenna design is more important in satellite systems when considering geometric coverage. Satellite VBF design should jointly take at least the above two aspects into account.

Operation orbit	Satellite communication systems	Multi-user access	Spot beams	Frequency bands
GEO	Inmarsat-4	FDMA	1 global beam; 19 wide spot beams; 193 narrow spot beams	L:1535～1542.5 MHz; 1636.5～1644 MHz
	Thuraya	TDMA/FDMA	250～300 spot beams	L:1626.5～1660.5 MHz; 1525.0～1559.0bMHz
LEO	Iridium	TDMA/FDMA	48 spot beams	L: 1621.35～1626.5 MHz
	Globalstar	CDMA	16 spot beams	L: 1610～1625.5 MHz; S: 2483.5～2500.0 MHz

TABLE 1. Some typical satellite communication systems and key techniques.

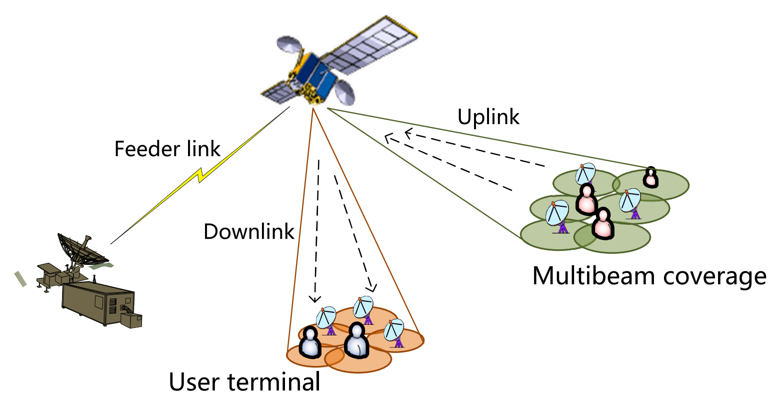

FIGURE 2. The architecture of a single satellite-terrestrial multi-beam system.

In early multi-beam satellite systems, beamforming techniques are an extension of well-known terrestrial MIMO beamforming techniques, such as linear precoding schemes [6]. These schemes perform well when the number of synchronously scheduled users is relatively small. However, since a larger number of users per beam is targeted in future communications, applying beamforming through the whole user set will bring significant inter-user interference and performance degradation. Therefore, multi-cast multi-group beamforming has been widely studied [6, 7]. Early multicast multi-group beamforming is based on a simple strategy where one spot beam serves multiple users, to which the same data symbols are broadcast. In recent years, more sophisticated schemes have been studied to further enhance spectral efficiency. For example, in [7], the precoding matrix is obtained based on block singular value decomposition (SVD), which aims to dynamically avoid inter-beam interference as well as to improve the performance.

Multiple Access Techniques in SINs

To make sure multiple users are connected to SINs without undue interference, multiple access techniques play a critical role. Similar to traditional multiple access, in a SIN architecture,

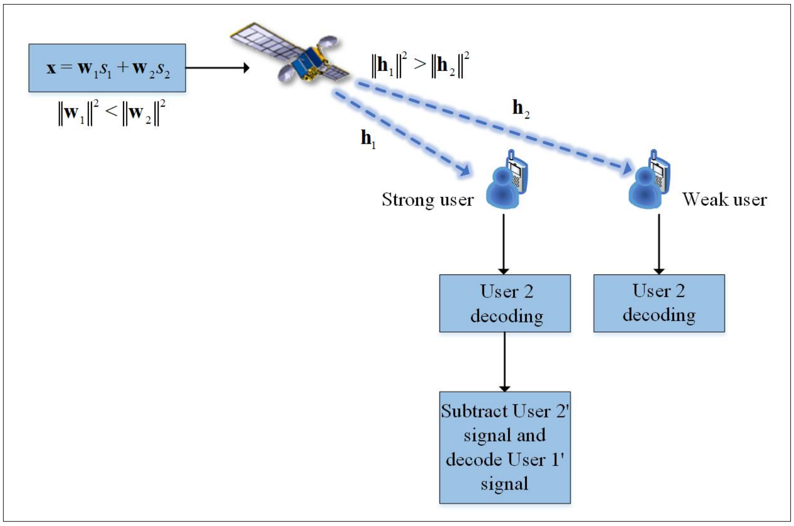

FIGURE 3. The architecture of satellite-NOMA with SCBF.

multiple access techniques should adapt to communication network dynamics and provide reliable service for different users under the limit of transmission power and radio spectral resources. In this section, we provide an overview of multiple access, while introducing the corresponding user scheduling strategies.

ORTHOGONAL MULTIPLE ACCESS

In multi-beam satellite communication systems, users in adjacent beams are allocated different radio channel resources. That is, the users covered by different spot beams connect to the SIN in an orthogonal manner such as via frequency-division multiple access (FDMA), time-division multiple access (TDMA), or code-division multiple access (CDMA). FDMA systems have multiple carriers that are separated in frequency at the satellite transponder. In a TDMA-based system, however, multiple signals from different users are separated in time slots while using an identical spectral resource. Using the same frequency band and time slot, the CDMA scheme distinguishes signals of different users by allocating different codes that are orthogonal to each other. In general, all these three techniques can be considered as orthogonal multiple access (OMA), in which channel resources are orthogonal among different users to mitigate inter-beam interference. Table 1 summarizes different access methods in the existing systems.

The OMA strategies are known as the fundamental techniques. To further enhance system performance, other multiple access techniques based on these three fundamental techniques, known as secondary access techniques, have been applied in satellite systems. Typical secondary access techniques include the demand-assigned multiple access (DAMA) and space-division multiple access (SDMA). According to user demands, the DAMA method dynamically allocates transmission resources (in time slots or frequency channels), where TDMA or FDMA is used to preassign channels. SDMA can employ any of the three basic techniques to physically separate signals from/to different users, and has been widely used in conjunction with the MIMO technique in multi-beam satellite systems. In order to improve system capacity, the optimization of SDMA is usually jointly considered with beamforming strategies in SINs.

NON-ORTHOGONAL MULTIPLE ACCESS

Although full frequency reuse and multi-user scheduling in one satellite spot beam guarantee higher system throughput, intra-beam interference should be considered as there is no sufficient degree of freedom for the satellites to reliably support all terminals. Hence, a trade-off between capacity and inter-user interference should be evaluated. Researchers are motivated to search for more advanced multiple access solutions to mitigate interference, while guaranteeing the system sum-rate.

Non-orthogonal multiple access (NOMA), as one of the potential multi-user access techniques in 5G, has received considerable research attention. Different from OMA, in NOMA, signals of different users are multiplexed via superposition coding in the power domain before transmission, and then are decoded via successive interference cancellation (SIC) at the receivers. Therefore, higher spectral efficiency can be achieved compared to that in OMA.

The implementation of NOMA in satellite communication systems is discussed in [8] with the architecture shown in Fig. 3. With the inspiration of NOMA, a two-user-based beamforming algorithm with superposition coding (SCBF) is proposed to improve throughput performance under quality of service (QoS) constraints. In the study, the superposition coding is applied in conjunction with SIC to successfully decode the signals for two users in the same beam. It is shown that the decoding order in SIC has a non-negligible impact on the user throughput. Clearly, the second decoded signal experiences less interference and thus can have a higher transmission rate.

The preceding NOMA scheme is the power-domain NOMA (PD-NOMA), which is the basis of other advanced NOMA techniques. Except PD-NOMA, NOMA concepts have a high potential for 5G multiple access, such as sparse code multiple access (SCMA), multi-user sharing access (MUSA), pattern-division multiple access (PDMA), and lattice partition multiple access (LPMA). The last three NOMA schemes are known as multi-carrier NOMA (or hybrid NOMA), where OMA is used to avoid inter-group interference and NOMA is implemented among the users within a single group. SCMA and PDMA are practical forms of multi-carrier NOMA that achieve a favorable trade-off between system performance and computational complexity. Hybrid NOMA is a promising multiple access technique to serve larger user groups and improve network capacity in multi-beam satellite communication systems.

The strengths of NOMA are apparent, even though practical application of NOMA in SINs faces challenges such as the computational complexity of SIC at the receiver side. Moreover, in order to take advantage of NOMA, efficient resource allocation (including power allocation and user scheduling) should be incorporated, which is more difficult to implement as compared to

OMA systems. Next, we provide a brief review of multi-user scheduling strategies.

MULTI-USER SCHEDULING

Multi-user scheduling strategies are closely related to beamforming and multiple access techniques. Similar to the beamforming design, a reliable scheduling strategy should provide high transmission quality to each scheduled user, achieve proper between spectral efficiency and fairness, and mitigate the inter-user/cluster interference.

As stated in the previous subsection, it is usually assumed that one user is served in each beam at a certain time slot for multi-beam satellites. For VBF systems, it is possible to consider user scheduling jointly with digital beamforming to improve system capacity as in terrestrial MIMO systems, although the benefits of multiuser diversity and scheduling are essentially neglected for most multibeam satellite systems in this scenario. However, it is challenging to consider user scheduling jointly with beamforming for multicast multi-group SINs where multiple users are chosen to share the same beam. Noting that scheduling users with similar or highly correlated channels can greatly improve the system performance, many researchers investigate channel vectors along with receiving signal-to-interference-plus-noise ratio (SINR). Meanwhile, some heuristic strategies have been proposed recently to provide better performance, such as the low-complexity full-channel-state-information-based user scheduling algorithm, which is studied jointly with beamforming for frame-based satellite communication systems [9].

COOPERATIVE TRANSMISSION IN SINS

In the presence of diverse network nodes in a SIN, cooperative transmission has the potential to enable multiple platforms to serve users flexibly and robustly. Via cooperative communications, the QoS of users with poor channel conditions can be improved without consuming too much additional resources [10]. In the following, we mainly focus on multi-user transmission structures using distributed satellite clusters (DSCs), satellites across different layers, and integrated satellite-terrestrial networks. Also, the cooperation among ground users is studied at the end of the section.

COOPERATIVE TRANSMISSION USING DSCS

In general, a DSC is made up of several satellites traveling on the same orbit [1], as shown in Fig. 4. To some extent, DSCs are an extension of single-satellite MIMO systems. With DSCs, a SIN can work flexibly and make a smart decision in real time according to the transmission requirements.

One motivation for DSCs is the limited space and spectral resources in satellite communications, especially in the GEO-based platforms. Therefore, allowing multiple satellites to share the same orbit window can greatly release the burden of orbit and spectral resources. However, how to properly share the same resource among different satellites is not an easy question. In this case, resource management appears as a critical issue in cooperative transmission. Assuming a multi-beam time-division multiplexing transmission, the power and time slot allocation is studied for downlink DSCs in [11]. The downlink transmission scenario has *L* DSCs to *N* user terminals, where each DSC consists of *M* satellites. A user can always be served by one satellite in a cluster under the assumption of an ideal interaction among clustered satellites. The optimization problem jointly captures the energy consumption and system capacity, under the limitation of transmit power and time slot allocation. An immune clone algorithm is presented to solve the joint optimization problem. Using the algorithm, high system capacity and energy-efficient allocation can be achieved with a fast convergence rate.

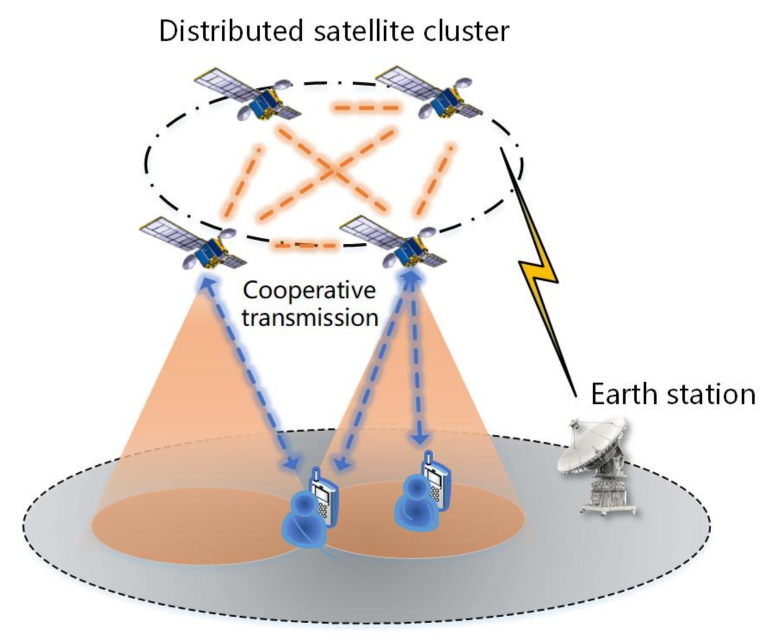

FIGURE 4. An illustration of cooperative transmission using a DSC.

COOPERATIVE TRANSMISSION ACROSS DIFFERENT NETWORK LAYERS

Due to the severe attenuation of GEO communication, hybrid satellite communication using satellites moving in different orbits has been analyzed. In [12], cross-layer cooperative transmission approaches using GEO and LEO satellites are studied where the LEO platforms help to relay signals. The proposed schemes consist of two phases, that is, from a GEO satellite to LEO satellites and from LEO satellites to users. Since a GEO satellite can directly communicate with a number of LEO satellites, how to select a relay has been studied to enhance system performance. Besides, recognizing the abundant spacial resources in the stratosphere, high altitude platforms (HAPs) such as airships and UAVs have received extensive attention in building SINs [13]. The architecture of integrated satellite/HAP systems to overcome a long-distance satellite link is also emphasized.

COOPERATIVE TRANSMISSION IN INTEGRATED SATELLITE-TERRESTRIAL NETWORKS

Thanks to the large service area coverage of SINs, satellite or other near-space-based communication networks can be utilized as a supplement to terrestrial networks for wireless communication services. In [14], a satellite-terrestrial cooperative transmission strategy, shown in Fig. 5, is studied to support multiple ground users. To fully exploit the spacial degree of freedom, multiple antennas

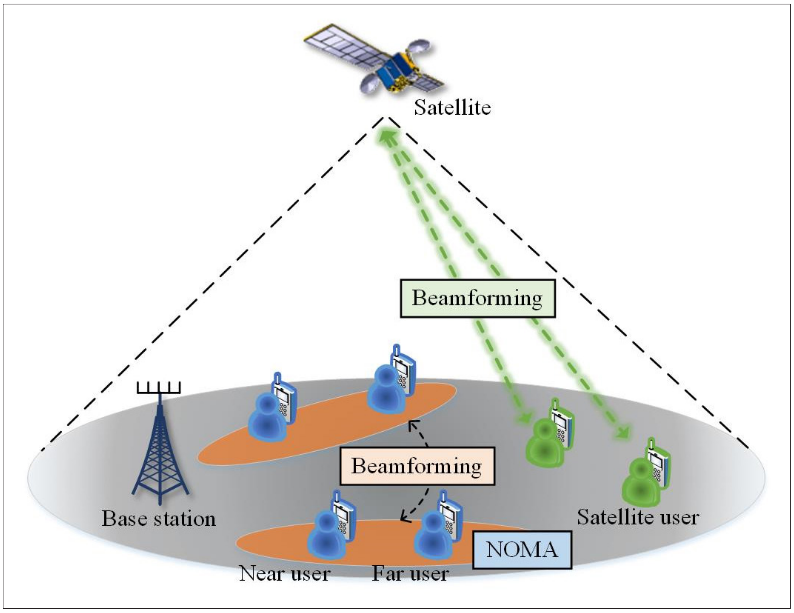

FIGURE 5. NOMA-aided beamforming strategy in an integrated satellite-terrestrial network.

are deployed at the base stations (BSs) and the satellite where beamforming schemes are utilized to offer interference-free downlink transmission. In this scheme, users with better satellite channels $\mathbf{h}$ and poor BS channels $\mathbf{f}$, that is, larger $||\mathbf{h}||/||\mathbf{f}||$, are served by the satellite network. Moreover, with a pairing strategy, users with highly correlated channel conditions can be categorized into groups. Then users within a group connect to a BS using the NOMA approach. Under the proposed NOMA-aided framework, resource optimization is further considered to improve the total system capacity. As a result, the integrated network enables more users access and achieves noticeable performance enhancement in comparison with the pure ground-based network.

COOPERATIVE TRANSMISSION AMONG GROUND USERS USING A NOMA SCHEME

Cooperation among users has also been widely studied. With the purpose of improving the transmission quality of users in a weak channel condition, a cooperative NOMA approach is proposed in [15], where the strong user acts as a relay. In the first time slot, the satellite broadcasts a superimposed signal for two users. Thanks to the power domain multiplexing, the two users can decode their own data with a SIC receiver. Since the information for the weak user is extracted first at the strong user receiver, it will be pushed forward to the weak user in the second time slot. To evaluate the performance of the scheme, the ergodic capacity expression is derived and the advantages are confirmed by numerical results.

CONCLUSION

In this article, the application of SIN for multiple user transmission has been presented. For an overview of SINs, first, we discuss the SIN architecture consisting of satellites, high altitude airships, and UAVs. Then, by recognizing the performance enhancement via exploiting the spacial degree of freedom, multiple-antenna techniques and the different accessing methods in SINs are presented. Finally, cooperative transmission techniques based on various platforms are investigated to take full advantage of spatial diversity in a SIN.

In summary, using the beamforming technique enabled by multiple-antenna equipment, multiple-user transmission within an identical frequency band and time slot can be realized, which increases the spectral frequency while suppressing the inter-user interference. In multi-user access schemes, a NOMA-based technique provides a spectrally efficient solution by exploiting advantages of resource sharing. In addition, cooperative transmission among different SIN nodes can improve the coverage performance as well as manage resources intelligently.

ACKNOWLEDGMENT

This work was supported in part by the Sichuan Provincial Military-Civilian Integration Industry Development Special Fund Project (No. ZYF-2017-71), in part by the Sichuan Provincial Major Science and Technology Projects (No. 2018GZDZX0022), in part by the State Key Program of National Natural Science of China (Grant No. 71731001), in part by the National Key Research and Development Program of China (Grant No. 2017YFB0503002), and in part by the Development Foundation of the 54th Research Institute of China Electronics Technology Group Corporation (No. XX18114T001).

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