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Interference management in 6G space and terrestrial integrated networks: Challenges and approaches

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Abstract: The Space-Terrestrial Integrated Network (STIN) is considered to be a promising paradigm for realizing worldwide wireless connectivity in sixth-Generation (6G) wireless communication systems. Unfortunately, excessive interference in the STIN degrades the wireless links and leads to poor performance, which is a bottleneck that prevents its commercial deployment. In this article, the crucial features and challenges of STIN-based interference are comprehensively investigated, and some candidate solutions for Interference Management (IM) are summarized. As traditional IM techniques are designed for single-application scenarios or specific types of interference, they cannot meet the requirements of the STIN architecture. To address this issue, we propose a self-adaptation IM method that reaps the potential benefits of STIN and is applicable to both rural and urban areas. A number of open issues and potential challenges for IM are discussed, which provide insights regarding future research directions related to STIN.

Key words: Interference Management (IM); power control; dynamic frequency sharing; Space-Terrestrial Integrated Networks (STIN)

1 Introduction

Compared with the current fifth-Generation (5G) wireless communication system, the next-generation system is expected to meet the high spectrum requirements and energy efficiencies with superior worldwide coverage[1]. Unfortunately, it is not a simple matter for the terrestrial systems alone to achieve the aforementioned performance goals, especially in areas of low population density and economic underdevelopment. Unlike the terrestrial communication system, the satellite communication network has a number of advantages, including broad coverage, strong adaptability to disaster events, and flexibility in grouping. Thus, this system is a very promising candidate for realizing worldwide coverage[2]. Recent developments in satellite technologies have been proven to provide greater availability and performance reliability compared to Long-Term Evolution (LTE) systems[3]. Therefore, we propose an appropriate and essential method for integrating the satellite communication system with terrestrial wireless networks via ground gateways to realize low-cost and high-speed transmission. In the proposed system, the ground gateways also serve as effective packet routers to the Internet backbone. The Satellite-Terrestrial Integrated Network (STIN) is expected to satisfy all the requirements of upcoming mobile communication networks.

Despite its many potential benefits, the STIN faces several tough challenges[4]. One of the biggest concerns is the co-channel interference between the satellites and terrestrial communication networks due to spectra sharing. For instance, the millimeter-wave band has been adopted in the newly deployed terrestrial communication network, which is also allocated to the

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satellite service now in operation. In the International Telecommunication Union Radiocommunication Sector, the frequency sharing issues between the satellite and terrestrial communication networks in the millimeter-wave band have been acknowledged and were reported at the 2019 World Radiocommunication Conference[5]. Unfortunately, as the interference in the STIN differs fundamentally from that in the terrestrial communication system, traditional Interference Management (IM) methods cannot be directly applied. For instance, the long communication distance and processing capacity constraints of the satellite communication system can cause problems, such as Channel State Information (CSI) feedback, which means that certain technologies, like precoding, cannot be used on the satellite. Also, the wide variety and densely deployed terrestrial network infrastructures have resulted in randomly distributed network topologies, which will inevitably cause the STIN interference in urban areas to be more serious than that in rural areas. Additionally, the significant dynamic characteristics of the satellite system also complicate IM schemes under the Quality of Service (QoS) requirement. Consequently, an efficient and effective IM method must be developed that takes into account the STIN architecture and types of interference.

Given the above facts, in this article, we introduce the features and challenges of IM in STIN, and then briefly summarize the IM approaches of the current space-terrestrial system. We then present a self-adaptation IM method for the future STIN. Lastly, we draw our conclusions and highlight open issues and challenges.

2 Feature and challenge of interference in STIN

In this section, we introduce the features of interference in the STIN, which differ significantly from those of traditional satellite or terrestrial communication systems. The challenges presented by these types of interference are discussed in detail.

2.1 Interference in STIN

Satellite User Equipments (UEs) in both rural and urban areas can benefit from the broad coverage, robustness, and reliability of satellite systems. As shown in Fig. 1, in rural area, the STIN architecture is relatively simple, i.e., terrestrial Base Stations (BSs) in the beams of satellites provide seamless coverage at a basic bit rate for a few users. In an urban area, however, there are various dense nodes, such as BSs, small cells, femtocells, and Remote Radio Heads (RRHs), which are randomly distributed for exchanging control signals and providing flexible network connection choices. This heterogeneous architecture results in a strong correlation among satellite UEs, complicates the structure of the terrestrial communication system, and makes IM a major concern.

In a traditional satellite communication case, it is generally assumed that there are few satellite UEs within the coverage area of the satellite, so that the major interference experienced by satellite UEs is from terrestrial BSs. However, this assessment is true only in rural areas. The ultra-dense network and multi-tier architecture of the STIN complicate its interference

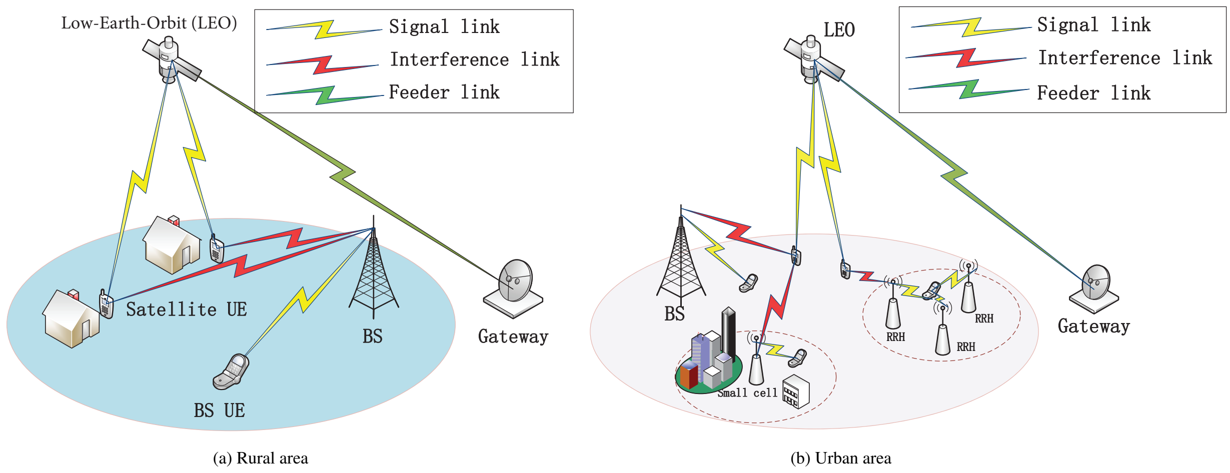


Fig. 1 STIN architectures in rural and urban areas.

environment. In particular, terrestrial BSs around satellite UEs are more densely distributed. As such, satellite UEs not only suffer interference from nearby BSs, but also are disturbed by other transmission nodes, such as small cells, RRHs, wireless access points, and even other BS UEs working in device-to-device mode. The existence of intensive access points can result in an extremely close spatial distribution of different interference transmitters that employ the same time-frequency resources. Thus, the channels between them and satellite UEs are similar, and the attenuation characteristics are identical. A dense network also severely shortens the communication distance. Therefore, only slight attenuation occurs in the interference power, which leads to the appearance of a Line-Of-Sight (LOS) component of the signal. This phenomenon also makes it difficult to distinguish LOS from reflected components. Overall, in terms of both the decoding complexity and the strength of the received signal, the interference environment has become more complicated, which has rendered techniques, such as resource allocation less effective.

2.2 Challenges caused by interference in STIN

There are many challenges associated with IM in the STIN. Some are similar to those in the terrestrial homogeneous network, and some are fundamentally different, which are discussed in detail below.

Interference estimation: Compared with conventional communication systems, the interference distribution in STIN is difficult to estimate for the following reasons. First, the heterogeneous nodes in the terrestrial networks are deployed to satisfy the traffic demands of BS UEs. As a result, it is very challenging to estimate the distribution of interference, which makes it difficult to coordinate strategies to address interference. Second, satellite UEs are more susceptible to strong interference by BSs than BS UEs, and the increasingly dense small cells increase the difficulty of addressing interference in a coordinated way. Third, the interference distribution is highly time-varying due to the mobility of both satellite UEs and BS UEs. Fourth, the long-range transmission from satellites makes this situation even harder to resolve. Estimating the various types of interference in an ultra-dense terrestrial network is also extremely challenging, especially when the antenna array is large, or the number of the fronthaul links is limited. Consequently, the interference levels of individual interferers are very difficult to distinguish. This brings problems with making decisions about whether the interference should be eliminated and which scheme is best to use in the STIN.

Information exchange: Due to the poor channel conditions and the long distance between space and the ground, information exchange between satellites and terrestrial BSs is difficult. Compared with the static (or quasi-static) terrestrial communication system, low-earth-orbit satellites can orbit the earth in less than 120 minutes. This highly time-varying characteristic poses a great challenge to real-time information exchange. A long transmission delay also increases the probability of packet loss. For instance, before the signals transmitted by satellites arrive on the ground, they suffer long-distance path loss, rain attenuation, atmospheric absorption, and other uncertainties. These factors inevitably weaken the strength of useful signals, leading to packet loss problems. As such, some IM techniques, such as precoding and power control, seem impossible to execute in satellites.

Multiple Input Multiple Output (MIMO) techniques in a satellite: The extensive application of MIMO technology makes it an attractive method for suppressing fading or interference. When channels are spatially uncorrelated, the data streams transmitted by multiple antennas at the source can be distinguished and successfully decoded by the intended receivers. Thus, spatial multiplexing gain can be substantially achieved[6]. However, in the STIN scenario, the communication satellite beams cover a broad range of areas. As such, if the terrestrial BSs and satellite UEs are located within the same satellite beam, their channels may be correlated, which will result in degradation of the multiplexing gain. In addition, due to the special structure of satellites, it is very difficult to install multiple antennas due to their limited load capacity. In this case, other advanced multi-antenna techniques, such as massive MIMO and network MIMO, which promise to increase throughput or data rates, will be more difficult to realize. Given these facts, without the benefits obtained by spatial multiplexing gain, the performance of MIMO will be compromised.

3 Implementation of IM in STIN

The new features and challenges in STIN make it difficult to mitigate interference by applying traditional IM methods. To develop an IM scheme suitable for the STIN, we first present a brief overview of existing IM techniques in space-terrestrial systems. Then, we design a self-adaptation IM method, which can target different types of interference in STIN based on the interference features and network conditions.

3.1 Overview of traditional IM schemes

Traditional space-terrestrial system IM techniques can be generally divided into two types with respect to the mechanism of the interference mitigation strategy, i.e., resource allocation and interference coordination.

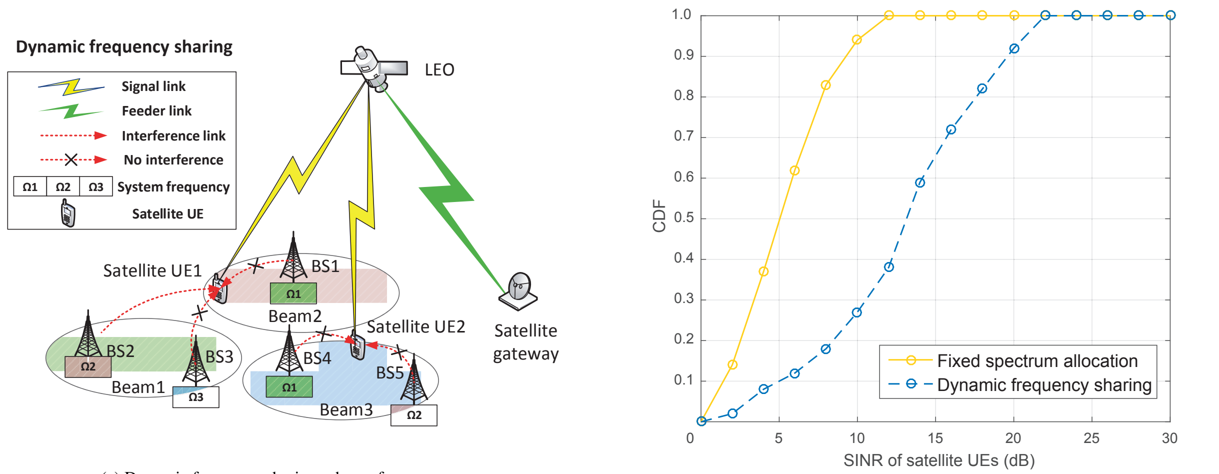
Resource allocation for IM: Attributing the main problem to a lack of available spectrum, the principle underlying conventional resource allocation is the partitioning of available resources into orthogonal proportions. Resource allocation techniques can be divided into three main types: spectrum utilization, power allocation, and region protection. (1) Spectrum utilization is used to protect the satellite system from strong terrestrial system interference. In this scheme, the satellite system allocates a continuous band of the idle spectrum to terrestrial communication networks[7]. (2) The fundamental idea of the power allocation scheme is to optimize the performance of the terrestrial communication network under its QoS constraints, such as its interference power threshold or the rate threshold of satellite UEs[8, 9]. (3) Inspired by cognitive radio in LTE, a region protection scheme has been proposed in which the satellite coverage area under a satellite spot beam is divided into several protected regions, according to the locations of both the satellite UEs and terrestrial BSs. To reduce the interference experienced by satellite UEs, terrestrial transmitters in a protected region are not allowed to use the same spectrum as the satellite system[10, 11].

Interference coordination for IM: Due to spectrum sharing and the randomness of interference, the principle of interference coordination is based on reducing interference or strengthening the useful signal. Typical interference coordination techniques include the interference-cancellation-based scheme and the cell-coordination-based scheme. (1) The basic idea of the interference-cancellation-based scheme is to subtract the interference signals from the mixed signals to guarantee the performance of the satellite system. Specifically, the satellite periodically reports the positions of its UEs to a terrestrial system. Based on the reported information and the frequency state, the terrestrial system then solves the coordination problem to maximize the average rate of the terrestrial network, and subjects to the interference constraint of the satellite link[12]. (2) In the cell-coordination-based scheme, terrestrial BSs with multiple antennas use a precoding scheme to strengthen their own useful signals or use a beamforming algorithm to reduce the interference component for satellite UEs[13].

3.2 Self-adaption IM method in STIN

Traditional space-terrestrial system IM techniques are designed for simple scenarios or specific types of interference. The network architecture of the future STIN has increased complexity, which means the IM technique must be carefully selected and switched dynamically to match the interference characteristics. Given the importance of this issue, we designed a self-adapting IM method for STIN, which can be applied to both sparse rural and dense urban networks. Three redesigned techniques are available for selection according to the UEs' locations, interference type, QoS requirements, and processing capabilities. The three redesigned techniques feature dynamic frequency sharing, spatial interference cancellation, and coordinated power control.

Dynamic frequency sharing: As shown in Fig. 2a, the satellite periodically listens to the location information of satellite UEs. If a satellite UE is located in a rural or other sparse area, the dynamic frequency sharing IM technique is triggered. BSs reuse the satellite bands allocated to the satellite point beams and the satellite frequency band allocated for each beam can be re-allocated to the BSs in its adjacent beams. For example, we consider a multi-beam satellite component with three spot beams operating in the different frequency bands $\Omega 1$, $\Omega 2$, and $\Omega 3$. Each satellite beam also includes a few terrestrial BSs that use the



(a) Dynamic frequency sharing scheme for sparse areas

(b) CDF of the SINR of satellite UEs with a fixed spectrum allocation and dynamic frequency sharing

Fig. 2 (a) Schematic of dynamic frequency sharing and (b) simulation results.

orthogonal frequency band of the beam that is covering them, e.g., BS2 and BS3 in the satellite frequency band Beam1 reuse bands Ω2 and Ω3, respectively. Using this scheme, the satellite UE suffers only slight interbeam interference from the BSs in its adjacent beams, such as Satellite UE1, and suffers no intrabeam interference from the BSs in the same beam, such as Satellite UE2. Then, to meet the required traffic demands for each beam or cell, the bandwidth and transmission power of the satellite and BSs are allocated according to the traditional resource allocation schemes. In dynamic frequency sharing, the frequency sharing condition, such as the UEs' locations or the available satellite band, is dynamically determined based on the reported information. If interference occurs between the terrestrial and satellite systems during frequency sharing, the sharing condition is changed. Additional available power volume of the interfering BS and the traffic demand of the satellite UE elements should be considered. When the interference is still too great, the cycle length of the dynamic frequency sharing should be reduced and the next frequency allocation procedure should be started or the coordinated power control scheme should be adopted. In this way, dynamic frequency sharing can achieve better spectrum utilization than the classic fixed spectrum allocation scheme.

Dynamic frequency sharing is capable of effectively avoiding intrabeam interference in sparse rural networks. Figure 2b illustrates the Cumulative Distribution Function (CDF) of the Signal-to-Interference and Noise Ratio (SINR) of satellite UE for performing fixed spectrum allocation and dynamic frequency sharing. The increasing probability of a special SINR for dynamic frequency sharing suggests the efficiency of interference cancellation. However, the interbeam interference may drastically degrade the performance in dense urban scenarios.

Spatial interference cancellation: The spatial Interference Cancellation (IC) technique is triggered to protect satellite UEs from the interbeam interference caused by the terrestrial BSs in its adjacent beams. First, the terrestrial BSs and satellite UEs dynamically exchange interference information and statistical performance indicators, such as UE locations, traffic demands, and the statistical channel status, during recent decades for the same resources. In practice, the CSI of the satellite downlink is obtained by using the returned training information, whereby the satellite transmits pilots to the satellite UEs for channel estimation. The satellite UE estimates the downlink channel and sends the estimated value to the satellite through the uplink. Then, the satellite periodically sends the channel direction information and CSI to the terrestrial BSs. Due to the channel estimation errors, high feedback delay, and particularly the CSI from another system in the spectrum sharing environment, the terrestrial BSs can only achieve an imperfect or statistical CSI of the satellite UE link. Therefore, traditional IM methods like coordinated beamforming cannot effectively deal with imperfect CSI cases. To reduce the impact of imperfect CSI, the satellite can enhance the pilot length or the pilot power transmitted to the satellite UEs. Lastly, as shown in Fig. 3, the process used by BSs and satellite UEs is as follows. (1) The BS uses large-scale multi-antenna precoding based on the position information and the estimated CSI of the satellite UE that experienced severe interference. (2) The satellite UE implements a series of successive interference cancellations to achieve spatial interference cancellation.

Figure 4 shows Matlab simulations of the overall outage probability performance of the proposed spatial interference cancellation scheme. The satellite altitude is assumed to be $d_L = 600$ km, with each BS having a coverage area with a radius of 500 m. The fading factor between the BS and UEs is assumed to be $\alpha = 3.7$. The typical antenna gains of the transmitters and receivers are $P_s G_t = 54.4$ dB and $G_r = 0$ dB, respectively. More specifically, as can be seen from Fig. 4, the spatial interference cancellation scheme with perfect CSI can achieve a better outage performance for both the BS UEs in Fig. 4a and the satellite UEs in Fig. 4b. Compared with the outage probability of BS UEs, there is a considerable gain for satellite UEs in this spatial interference cancellation scheme.

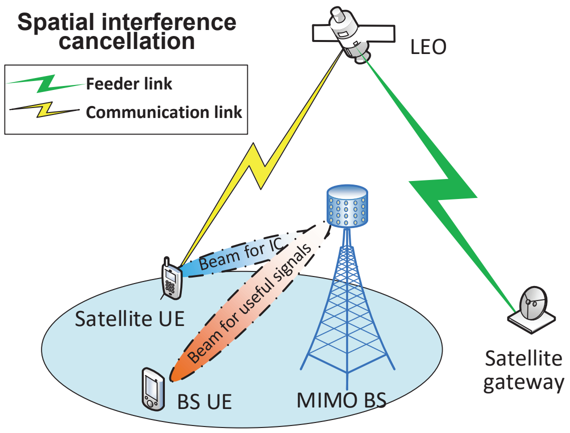
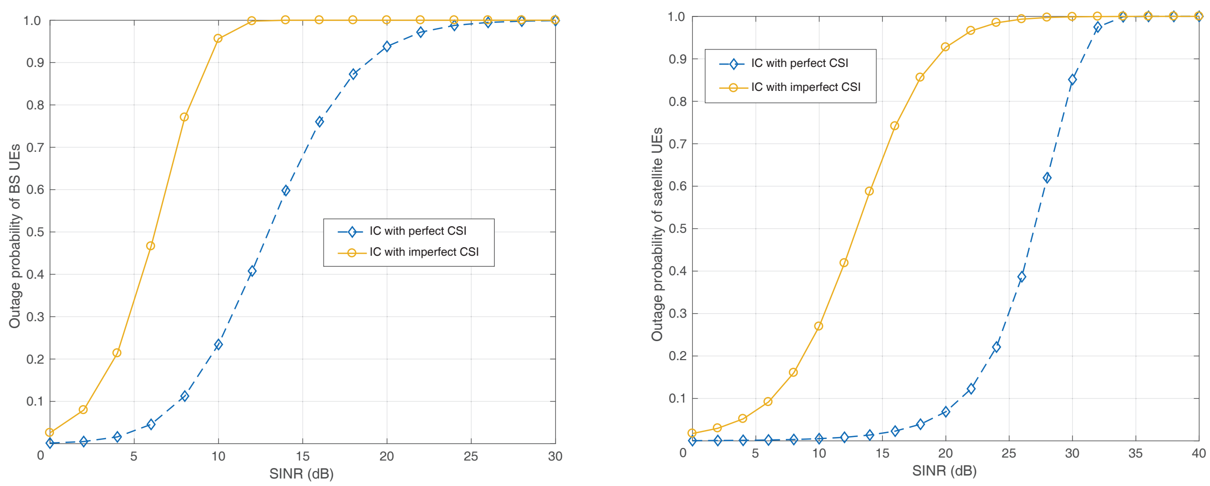


Fig. 3 Schematic of spatial interference cancellation for addressing interbeam interference.

Coordinated power control: To reduce interference from terrestrial BSs to satellite UEs in the same beam, satellite UEs periodically report their positions, channel status, and other information to the BSs. Based on all the information transmitted through the BSs fronthaul in the cloud, a large-scale centralized virtual precoding operation is performed. As shown in Fig. 5a, using the transmission precoding scheme, a null space is constructed to eliminate the downlink interference from the terrestrial BSs to the satellite UEs, which improves the STIN performance.

In ultra-dense networks, high demand for communication is periodic in many hot spots, such as office buildings. Since cooperation between terrestrial and satellite UEs is difficult to implement, here, we focus only on the cooperation of satellites with terrestrial BSs. The BS periodically detects the demand volume and communication performance of covered UEs, then controls the transmission power based on the



(a) Outage probability of BS UEs with perfect and imperfect CSI schemes versus the SINR

(b) Outage probability of satellite UEs with perfect and imperfect CSI schemes versus the SINR

Fig. 4 Outage probabilities of BS and satellite UEs with different schemes as a function of the SINR.

packet loss rate, throughput, and end-to-end delay. If the total demand volume of the BS remains larger than a preset threshold, which is determined by the available resources and the historical maximum practical capacity, and any of the three parameters related to transmission quality is reduced to less than the QoS thresholds, the system is determined to be in a high traffic state. In other words, the system configuration cannot support the current traffic state.

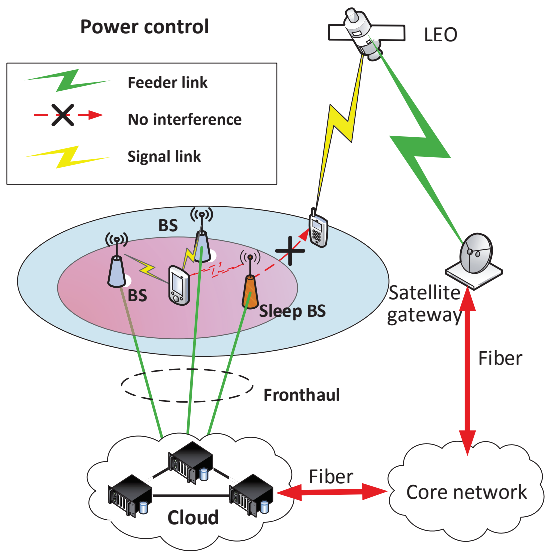
In response, the BS increases its transmission power and turns on other nearby idle BSs. Large-scale wireless resource scheduling is also conducted. In contrast, when the total demand for the BS is continuously less than the preset threshold, and the three parameters related to the transmission quality of the STIN are all higher than their QoS thresholds, the system is determined to be in a low traffic state. Then, as shown in Fig. 5, according to the energy efficiency index, the BS reduces or shuts down the transmission power when the UE switches to a nearby BS or satellite. In this way, the goal of reducing interference can be achieved by reducing energy consumption. Figure 5b shows a comparison of the cumulative distribution function of the SINR of Decentralized Power Control (DPC) for random access and coordinated power control, for a sleep status power of 24.4 dBW. The large throughput clearly suggests low interference, which confirms the effectiveness of the proposed coordinated power control.

4 Challenge and open issue

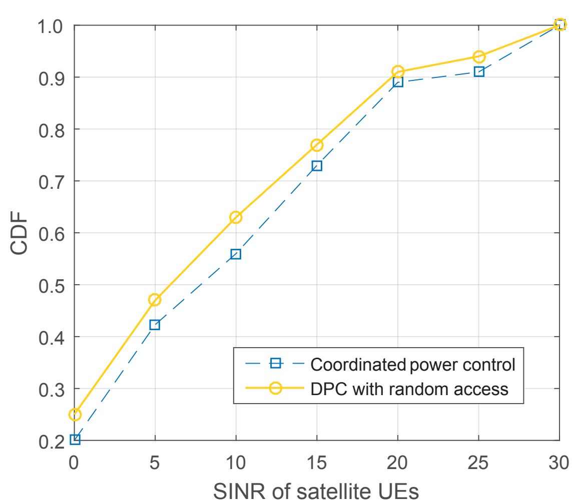
As discussed earlier, interference coordination and resource allocation can be used to effectively manage interference in the STIN and improve system performance. However, with ongoing advances in communication technology, wireless communication networks will face many new challenges, especially in the STIN, as satellite UEs are more likely to experience interference from BSs. Therefore, the development of strategies to intelligently manage interference in the STIN remains an urgent problem. In this section, we discuss several critical open issues in IM for the future STIN.

4.1 IM with artificial intelligence

Considering its complex configuration and new traffic requirements, the STIN cannot meet the demands of high-speed communication without a comprehensive artificial intelligence function. Therefore, artificial intelligence plays an indispensable role in the next-generation wireless communication system[14]. For example, Ref. [15] proposed a reinforcement-learning-based power control scheme to suppress downlink inter-cell interference and conserve energy for ultra-dense small cells, for which a deep-reinforcement-learning-based interference control algorithm is designed to further accelerate learning for ultra-dense small cells with a large number of active users. This scheme



(a) Coordinated power control for intrabeam interference



(b) Cumulative distribution function of the SINR of satellite UEs with decentralized power control and coordinated power control

Fig. 5 (a) Schematic of coordinated power control and (b) simulation results.

has been verified to be very effective. The utilization of artificial intelligence in STIN can enable flexible interference coordination and improve the spectrum and energy efficiencies relative to those obtained by the existing fixed resource allocation approach. Primarily, by interacting with the environment, artificial intelligence solves the problems of how to learn variations, classify issues, forecast future challenges, and find potential solutions.

Machine learning, as one of the most important subfields of artificial intelligence, has been extensively studied for application to the current wireless communication systems. For example, supervised learning is used to solve channel estimation problems in wireless networks. In addition, using cognitive radio technology, the dynamic transition of spectrum availability is modeled as a Markov chain to solve channel switching issues and thereby reducing interference in the main spectrum. Despite the obvious opportunities, the application of artificial intelligence to interference coordination in the STIN faces many challenges, especially with respect to data, which enables artificial intelligence to analyze trends and recognize patterns.

First, artificial intelligence is a technology that involves learning variations and analyzing data to solve problems, for which the modeling problems require large volumes of data. Therefore, before applying statistical methods to interference coordination in STIN, ordinarily, data must be gathered using a centralized method. However, to save time and process network data efficiently, a lot of storage and computing resources are needed, which inevitably place a great burden on the satellites and BSs. In addition, although BSs can easily acquire terrestrial UE data, a strategy for obtaining satellite UE data has not yet been established.

Moreover, data collection will undoubtedly bring new security concerns. If data processing and storage are not properly supervised, user identity information could be at risk. This poses a serious threat to information security when a large amount of user information is being collected. Ensuring system security and preventing data leakage are also great challenges for the application of artificial intelligence to STIN.

Another challenge is the design of a simple artificial-intelligence-based interference coordination method that can perfectly match data. Their derivation, which involves many parameters, can also be difficult to be read and some values may even be lost in practical applications. In this situation, an artificial-intelligence-based interference coordination method will have no obvious positive effect on IM for satellite UEs. Moreover, the use of complicated interference coordination models to solve problems will inevitably increase the computing burden on the satellites and BSs. As such, though the effectiveness of artificial intelligence in the future network is attractive, its high computational complexity and long training time must be urgently addressed.

4.2 IM with low energy consumption

Energy consumption has become one of the most important global issues. Although resource allocation can reduce energy consumption in the STIN, many challenges remain. Therefore, the development of ways to decrease interference and improve energy efficiency is critical for the STIN.

It is common practice for current terrestrial networks to improve energy efficiency and reduce interference by the use of a periodically switched on-off model[16]. In this setup, some lightly loaded BSs can be selectively switched to sleep mode. The core idea of this method is based on a hard assumption that the network load can be accurately tracked and provided to the corresponding BSs. However, the traffic load in the current terrestrial networks may experience significant spatial and temporal fluctuations. Therefore, another challenging issue in future STINs is how to accurately estimate spatial and temporal fluctuations.

Compatibility is another concern. Not all current terrestrial cellular networks support intelligent resource allocation schemes, and their network management structure must be reconfigured for their integration with satellite communication systems. For instance, a special control channel is required. In addition, when some BSs are switched to sleep mode, there is a significant negative impact on the QoS for terrestrial UEs, which cannot be ignored. For instance, although the communication performance for satellite UEs has improved, the terrestrial network blocking rate may increase when an excessive number of BSs are switched to sleep mode. Moreover, if the BS frequently alternates between sleep and active modes, the probability of BS outages will increase significantly, which will involve considerable cost.

4.3 IM with satellite user link and backhaul constraints

Although many measures are used to meet the capacity requirements of IM methods in the STIN, the ever-increasing demand for data will increase the pressure on both the satellite user link and backhaul link in the future. In fact, an ideal satellite user link (or backhaul link) with infinite capacity and low latency is practically impossible, so solutions to these issues must be devised.

For the satellite user link, the optimal solutions of spatial interference cancellation with nonideal satellite-ground link constraints are always Non-deterministic Polynomial-hard (NP-hard). In other words, it is very challenging for an existing STIN to reduce interference in polynomial time as the number of satellite and terrestrial UEs increases. Therefore, a sub-optimal solution with low complexity must be proposed for the future STIN. For the backhaul link, with the deployment of heterogeneous nodes, i.e., BSs, small cells, and RRHs in terrestrial communication networks, an advanced self-organizing function should be adopted to enable the terrestrial nodes to work intelligently and automatically. In addition, the limited backhaul capacity also affects the performance of IM methods as large volumes of data and control signals must be exchanged between BSs for their coordination. As such, an effective algorithm with low complexity under limited capacity and nonzero latency constraints is required to improve the performance for STIN.

5 Conclusion

In this article, we investigate the current issues and challenges of IM in the STIN and then briefly summarize the existing predominant IM techniques. We propose a self-adaptation IM method based on three redesigned techniques, namely dynamic frequency sharing, spatial interference cancellation, and coordinated power control. Compared with traditional IM methods, the proposed self-adaptation IM method can be applied to both sparse rural and dense urban networks according to the UEs' location, type of interference, QoS requirements, and processing capabilities. In addition, potential research directions and open issues are discussed, including artificial intelligence, energy consumption, and satellite user link/backhaul constraints. In summary, we anticipate that advances in this area will continue and bring IM techniques for the STIN to new frontiers.

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