Cooperative Resource Management for Cognitive Satellite-Aerial-Terrestrial Integrated Networks Towards IoT

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ABSTRACT With the ubiquitous deployment of Internet-of-Things (IoT) devices and applications, satellite-aerial-terrestrial integrated network (SATIN) is regarded as a promising candidate to facilitate global IoT with diverse services. To accommodate the explosive demands of IoT within crowded spectrum, we focus on the cognitive radio based SATINs where spectrum sharing is enabled among satellite, aerial, and terrestrial network segments, and devote to efficient resource management. Specifically, by reviewing main challenges that the characteristics of cognitive SATINs and the requirements of IoT bring to resource management, we analyze the potential of incorporating cooperation into cognitive SATINs for future intelligent IoT. Then, we propose a cooperative beamforming scheme to facilitate secure and energy-efficient IoT communications under limited energy for open channel environments in cognitive SATINs. Simulation results validate the superiority of cooperation resource management in cognitive SATINs towards IoT.

INDEX TERMS Satellite-aerial-terrestrial integrated network, cognitive radio, Internet-of-Things, cooperative resource management.

I. INTRODUCTION

Being a worldwide network of interconnected objects with standard communication protocols, Internet-of-Things (IoT) allows people and things to exchange information anytime, anyplace, with anything and anyone [1], [2]. With the unprecedented development of the fifth-generation (5G) communication systems, various IoT applications in urban area, such as smart cities, intelligent transport, and pollution control, can be effectively supported by terrestrial network with densely deployed infrastructure and advanced network/access architecture [3]. Moreover, since satellite communications can provide coverage for remote areas without backbone connectivity, it is becoming an indispensable part in IoT applications as wildlife monitoring, etc [4], [5]. However, limited by scarce orbit resources, high maintenance costs, and large round-trip delay, conventional satellite-terrestrial

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hybrid networks cannot meet various service requirements of future global IoT in an efficient and cost-effective manner. Alternatively, owing to the relatively low cost and flexible movement, aerial communications based on unmanned aerial vehicles (UAVs) is emerging as an attractive paradigm for IoT [6]. Specifically, UAVs can quickly re-establish connectivity in disaster-struck regions by acting as substitutes for the damaged terrestrial infrastructure. Moreover, UAVs can intelligently change their locations on-demand to relieve the burst traffic demands of terrestrial networks. To accommodate diverse services with different quality of service (QoS) requirements in IoT, it is highly demanding to incorporate UAVs into satellite terrestrial networks and construct a triple-tier satellite-aerial-terrestrial integrated network (SATIN) [7]–[9].

Although SATINs offer a promising architecture for global IoT, the spectrum scarcity restricts the service capabilities provided by the SATIN. On one hand, with the ubiquitous deployment of IoT devices and applications, a large

amount of data is introduced into the network and causes the spectrum scarcity issue. On the other hand, conventional spectrum management methods are not flexible and reasonable. In particular, according to ITU-R, only 500 MHz (19.7-20.2 GHz for the downlink and 29.5-30 GHz for the uplink) is exclusively available for satellite links, and the rest Ka-bands allocated to satellite communications are shared with terrestrial Fixed Services (FSs). Moreover, traditional aerial communications have been operating on unlicensed spectrum bands, which is becoming overcrowded [10]. The exclusive regulations of spectrum assignment and static spectrum allocation cause inefficient and unbalanced utilization of the spectrum, which intensifies the contradiction between the continuous growth of interconnected objects in IoT and the limited spectrum resources. In this regard, cognitive radio (CR), which can alleviate the spectrum scarcity problem and improve spectrum efficiency by dynamic spectrum access, is regarded as a promising solution for IoT applications [11], [12]. Motivated by the benefits of employing CR into satellite-terrestrial and aerial-terrestrial networks, as well as the bright application prospects of the IoT, we incorporate CR into the SATINs to effectively use the network resources and satisfy the enormous connectivity demands in IoT.

As a main functional component of the CR based SATINs towards IoT, efficient spectrum sharing plays a significant role in increasing the system spectrum efficiency [13]. In regard to spectrum sharing, three modes are enabled in such systems, i.e., underlay, overlay, and interweave. The underlay mode, in which the cognitive system is allowed to reuse the spectrum licensed to the primary system without causing excessive interference at the primary user, is especially attractive due to its effective spectrum utilization [14]. On account of this point, we focus on the underlay mode based cognitive SATINs where spectrum reusing is enabled among satellite, aerial, and terrestrial network segments to satisfy the huge demand of IoT for spectrum. To achieve friendly coexistence among satellite, aerial, and terrestrial network segments, there are some new challenges of resource management in cognitive SATINs towards IoT. Firstly, it is imperative to fully utilize the advantages of each network segment to support diverse IoT services with various QoS requirements. Additionally, complex interference scenarios in cognitive SATINs, resulting from hybrid co-channel interference (CCI) (inter-segment CCI and intra-segment CCI) and asymmetry of uplink and downlink interference links, make it necessary to design a fine-grained interference management strategy.

Considering the onefold capability of each network segment with limited resources is insufficient to serve IoT effectively, in this paper, we study the coordination and cooperation among multiple network segments for efficient resource management in cognitive SATINs towards IoT. From the prospective of IoT characteristics and application requirements, we firstly present the architecture of cognitive SATINs and analyze how the cognitive SATINs serve the IoT. Based on which, we review the key issues and related challenges for efficient resource management in cognitive SATINs towards IoT. Taking account of the inherent open channel environments of space network and the increased energy consumption in 5G, we give a case study regarding cooperative beamforming in cognitive SATINs to enhance the communication security and energy efficiency of IoT. Simulation results validate the superiority of cooperation resource management in cognitive SATINs towards IoT, which provides a solution to facilitate global IoT through cognitive SATINs and can be extended to various IoT cases.

II. RELATED WORKS

For resource management related to cognitive SATINs towards IoT, existing literatures can be categorized into two parts. One is the resource management in single-tier satellite/aerial/terrestrial networks for various IoT scenarios and the other one is the resource allocation for eliminating interference caused by spectrum reusing in cognitive satellite/aerial-terrestrial networks. Related literature reviews are presented as follows.

A. RESOURCE MANAGEMENT IN SATELLITE/AERIAL/TERRESTRIAL NETWORKS TOWARDS IOT

In terrestrial cellular networks, to improve the resource utilization as well as minimizing the energy consumption of IoT system, many resource allocation schemes have been proposed, such as bandwidth allocation [15], joint optimization of sub-carriers and transmit power [16], [17], and joint allocation of resource blocks and transmit power [18].

In UAV assisted IoT communications, considering the limited power and energy of UAV and IoT nodes, some researchers focused on optimizing resource allocation to reduce power overhead and prolong network life [19]–[24]. Aiming at minimizing the overall energy consumption for accomplishing tasks, the authors in [19] considered a UAV-aided edge computing scenario and studied the task offloading problem between the IoT mobile devices and the UAV. In [20], to enable reliable uplink communications for IoT devices with a minimum total transmit power, the authors proposed a novel framework for jointly optimizing the three-dimensional (3D) placement and the mobility of the UAVs, device-UAV association, and uplink power control. Assuming that UAV acts as a mobile relay in the IoT, the authors in [21] jointly optimized the UAV's flight trajectory as well as energy and service time allocations for packet transmissions to minimize the average peak age-of-information. For UAV assisted IoT communications in disaster rescue scenarios, the authors in [22] proposed a UAV network access and a resource allocation scheme to maximize the number of IoT devices. In a cognitive UAV network, the authors in [23] proposed a data dissemination scheme to maximize the minimum bits received by the IoT devices while guaranteeing the number of slots used for transmission not exceed the maximum allowable interfering slots. In [24], the authors employed the simultaneous wireless

information and power transfer (SWIPT) technology in UAV assisted IoT systems, and investigated the joint optimization of power allocation and trajectory design of the UAV to support infrastructure-starved IoT services.

In satellite assisted IoT communications, the authors in [25] proposed a deep learning-based long-term power allocation scheme to achieve the optimal power allocation and decoding order for non-orthogonal multiple access link. In [26], in order to improve the resources allocation efficiency of high-throughput satellite systems towards IoT, the authors constructed a new mathematical model for solving the trade-off between the transmit power and beam directivity. Moreover, aiming at improving the spectral efficiency of the satellite-based IoT, the authors in [27] proposed a novel forward-link multiplexed scheme based on constellation coding, by which the signals of different users can be transmitted simultaneously using the same frequency band. Motivated by the lower round trip time and lower propagation loss of LEO satellite, the authors in [28] proposed a narrow-band IoT (NB-IoT) architecture over low earth orbit (LEO) satellite, and devoted to reduce the high values of differential doppler through resource allocation approach.

B. RESOURCE MANAGEMENT IN COGNITIVE SATELLITE/AERIAL-TERRESTRIAL NETWORKS

To alleviate the spectrum scarcity problem in space network, existing literatures mainly employ CR based spectrum reusing among satellite, aerial, and terrestrial network segments and focus on the interference management caused by inter-segment CCI through effective resource allocation.

For cognitive aerial-terrestrial networks, the authors in [29] proposed an energy efficient 3D positioning scheme along with power allocation approach to reduce the energy consumption of flying and communication of UAVs while guaranteeing the QoS of the primary users. To demonstrate the effects of integrating UAV based aerial base station (BS) into cellular networks, the authors in [30] theoretically analyzed the coverage probability of the cellular network that serves both aerial and ground users. Considering the coexistence between the UAV and underlaid device-to-device (D2D) users, the coverage probability and system rate were investigated in [31]. Taking the constraints of interference and the mobility of UAV into account, the authors in [32] optimized the trajectory of UAV and transmit power of both terrestrial BS and UAV to maximize the achievable rate of terrestrial users. For the scenario where UAV and terrestrial users are served by the cellular network, the transmit rate of UAV and power allocation were optimized to maximize the weighted sum-rate of the UAV and terrestrial users [33].

For cognitive satellite-terrestrial networks, the authors in [34] presented several basic scenarios and system models, where satellite and terrestrial networks can operate as primary and secondary systems, respectively, or vice versa. In [35], the authors designed a cognitive zone to guarantee the primary satellite communication while providing high service availability to secondary terrestrial users. The authors

in [36] proposed a joint carrier-power-bandwidth allocation scheme to maximize the throughput of the satellite network, which operates in microwave frequency band. In [37], the authors introduced a power allocation scheme that can optimize the effective capacity of terrestrial communications for given QoS requirements while guaranteeing the outage probability (OP) of satellite communications. In [38], the authors conducted power allocation to maximize the achievable rate for cognitive hybrid satellite-terrestrial networks with amplify-and-forward (AF) relays. Besides, for real-time satellite applications in cognitive satellite-terrestrial networks, the authors in [39] conducted power control to maximize the delay-limited capacity without degrading the communication quality of the primary terrestrial user.

III. COGNITIVE SATINS ARCHITECTURE TOWARDS IOT

Network integration is an expecting trend to satisfy diverse requirements of future IoT. Fig. 1 shows the collaborative cognitive SATIN architecture, which consists of satellite, aerial, and terrestrial network segments described as follows:

- The satellite network segment including geostationary orbit (GEO), medium earth orbit (MEO), and LEO satellites with large coverage capability are mainly used for broadcast and multicast services in IoT. To realize the next generation Terabit/s satellite system within the 2020 horizon, satellite networks is evolving to a high throughput satellite (HTS) system [40]. Equipped with an array fed reflector, the HTS system can produce a large number of beams (e.g., more than 100), which can support the spatial multiplexing communication and enhance the capability that satellite networks provide for IoT.
- With lower altitude (about tens of kilometers above the earth) and flexible movement, the aerial network segment, which contains UAVs, unmanned airships, and balloons, can boost capacity in hotspot areas and provide timely connectivity for emergency scenarios. Considering that the service capability of a single UAV is limited, it is of great significance to form a UAV swarm through multiple UAV networking for data collection and distribution on a large range of IoT networks.
- Along with the development of 5G communications, ultra-densely deployed cellular cells are emerging in terrestrial network segment to facilitate various IoT services. According to specific key performance indicators (KPI) requirements, IoT services can be categorized into two types: ultra-reliable and low-latency communications (URLLC), and massive machine-type communications (mMTC).

Regarding to IoT with worldwide applications, massive devices, and miscellaneous service requirements, coordination and cooperation among satellite, aerial, and terrestrial network segments in term of spectrum resources and network structure are indispensable to facilitate the evolution of IoT. Moreover, for such a multi-layer, heterogeneous, dynamic,
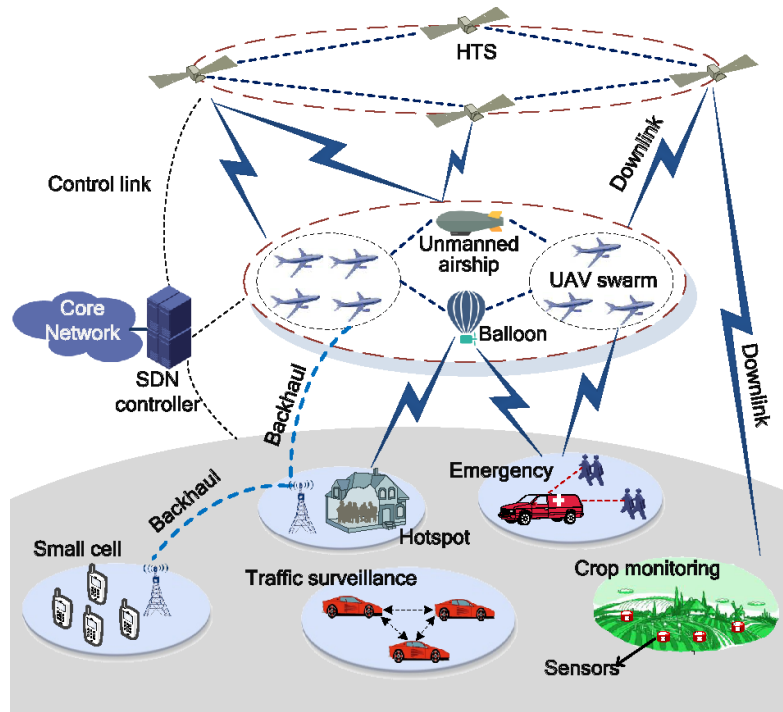
FIGURE 1. The architecture of cognitive SATINs towards IoT.

and complex network, a software-defined network (SDN) control center is deployed to implement logically centralized network management and intelligent cognition among multiple network segments.

From Fig. 1 we can see that, there are not only different types of uplink that back haul the gathered IoT data to remote control center, but also various downlinks from satellite, aerial, and terrestrial nodes that forward information, such as control signaling, from remote control center to IoT devices. In the following, we analyze three typical scenarios to illustrate the prospects of segment collaboration of cognitive SATINs in IoT.

A. CONTINUOUS COVERAGE FOR IOT WITH DIVERSE TRAFFICS

With the aid of cognitive SATINs, trillions of sensors and devices can be connected, paving the way for building an intelligent IoT. In fact, due to the difference of satellite, aerial, and terrestrial network segments in transmission delay, flexibility, and altitude, these network segments have their respective roles in IoT which can be distinguished by identifying domain-specific requirements, key features, and criticality of various IoT scenarios. Specifically, satellites are mainly used for application where devices are sparsely located in remote areas, e.g., remote substation automation. For application with stringent delay requirements, e.g., unmanned ground driving, UAVs have advantages in realizing real-time data acquisition. Moreover, for sensors that are typically unable to transmit over a long distance due to their energy constraints,

UAVs can dynamically move towards IoT devices following a well-designed trajectory and even implement wireless charging along with information transmission. For densely populated areas or indoor scenarios where line-of-sight (LoS) links are unavailable to satellites and UAVs, infrastructure based terrestrial networks can provide broadband and reliable wireless access for IoT devices. Thus, global IoT can only be achieved through network integration of satellite, aerial, and terrestrial segments.

B. COST-EFFECTIVE AND FLEXIBLE DISASTER-RESILIENT IOT NETWORKS

Resilience and high availability are critical for IoT networks, especially for some key mission data. Unfortunately, in disaster situations caused by earthquake, flood, or forest fire, etc., the terrestrial infrastructure may be destroyed, resulting in communication failure and only incomplete information is available to rescue teams. In this situation, satellites/UAVs can operate as compelling candidates to provide backup connectivity for the damaged on-ground infrastructure. Equipped with cameras and sensors, satellites and UAVs can provide an aerial vision over large area and capture high quality data of images and videos. Afterwards, these videos and images can be communicated to users or rescue teams on ground for real-time search and rescue. Especially, benefiting from flying nature, flexible deployment, low maintenance cost, and high maneuverability, UAV based aerial networks can offer timely and temporary wireless access service for disaster-affected areas and emergency situations. As a result,
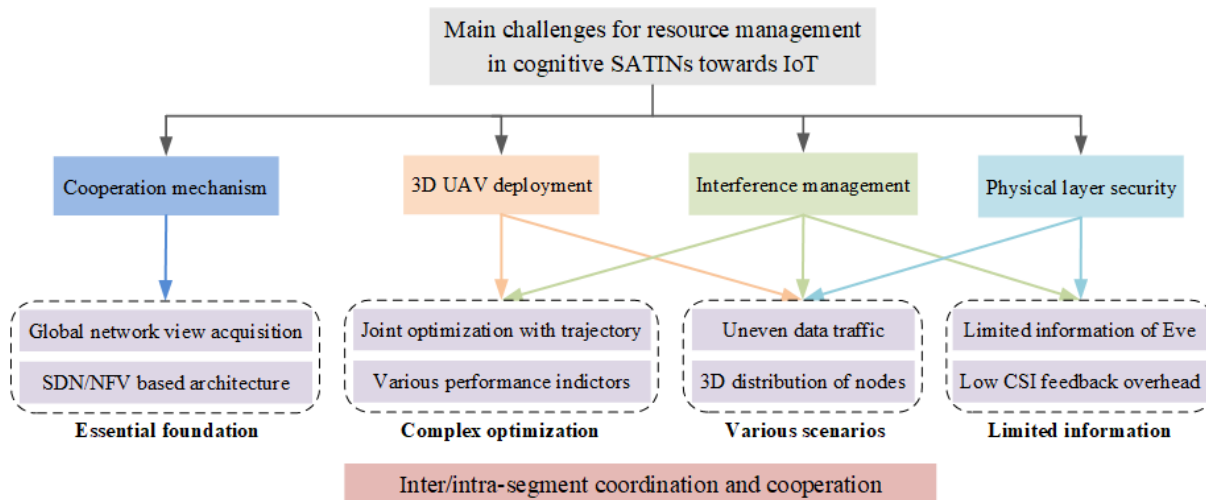
FIGURE 2. Main challenges for resource management in cognitive SATINs towards IoT.

the cognitive SATIN provides a solution for cost-effective and flexible disaster-resilient IoT networks.

C. HYBRID WIRELESS BACKHAULING FOR MASSIVE IOT DATA

The rapid increasing of IoT devices and traffic will impact not only the radio access technology, but also the backhauling mechanism. A promising solution is to deploy ultra-dense small cells that can mesh together with mmWave technology. However, the spectrum band between cellular access and the core networks is becoming overcrowded and traffic is approaching to overload, the standalone terrestrial network cannot satisfy the high throughput backhauling demands. In this case, satellites and UAVs based backhaul links in the integrated network can provide backup connectivity to divert traffic from terrestrial congested areas during peak-time or in the case of failure. Consequently, the triple-tier SATIN supply a hybrid wireless backhauling architecture for future IoT networks. To adequately utilize the backhauling path redundancy offered by SATINs, delicate traffic engineering should be exploited in terms of QoS requirements of services, link status, and energy consumption, etc.

IV. KEY ISSUES FOR RESOURCE MANAGEMENT IN COGNITIVE SATINS TOWARDS IOT

As the cognitive SATIN is a typically multi-layer, heterogeneous, and dynamic network, it is challenging to conduct efficient cooperative resource management in such a complex network. Moreover, IoT with miscellaneous service requirements poses new research challenges for the cooperative resource management. The challenges introduced by cooperation among different devices in different network segments not only lie in how to implement the cooperation technology itself, but also are involved in other key issues, e.g., 3D UAV deployment, interference management, and physical layer security. Fig. 2 illustrates key issues and related technological

challenges to achieve friendly coexistence among different network segments as well as efficient resource utilization of SATINs towards IoT.

A. COOPERATIVE MECHANISM

In the considered cognitive SATINs, to implement cooperative and coordinated resource management through the deployed SDN controller, massive inter/intra-segment state information exchange is the cornerstone. For such a multi-layer, heterogeneous, dynamic, and complex cognitive SATIN, how to acquire the global network view with the limited resources is the crucial issue need to be solved. Leveraging the concepts of software and virtualization, incorporating network function visualization (NFV) into SDN has become a promising solution for cooperative resource management in SATINs to improve the system flexibility, customization, and scalability. However, to realize the SDN/NFV enabled cooperative resource management, an efficient resource management architecture based on network slicing is another main challenge.

B. COORDINATED 3D SPATIAL-TEMPORAL DEPLOYMENT OF UAVS

Node deployment is the initial stage for network formation and its performance seriously influences subsequent resource optimizations.

In SATINs, since UAVs act as the complement of existing satellite-terrestrial networks to enhance IoT services, the UAV deployment should be coordinated with satellite and terrestrial segments, rather than an independent issue. Therefore, when deploying UAVs, it is firstly indispensable to investigate the spatial-temporal coverage characteristics of existing satellite-terrestrial networks, which is critical for achieving seamless coverage as well as avoiding duplicate coverage. Specifically, the spatial-temporal coverage characteristics includes the spatial coverage characteristics at a

certain moment and the continuity of coverage for a given area over a period of time. Secondly, data traffic in IoT network is temporally (day and night) and spatially (traffic burst due to events) uneven. Thus, it is crucial to conduct coordinated on-demand UAVs deployment in SATINs according to IoT traffic distributions.

Due to the characteristic that UAVs operate in 3D space, both horizontal position and altitude should be taken into account to enable a mature 3D deployment of UAVs. Although a higher probability of LoS transmission can be obtained by increasing the altitude of UAVs, it renders larger pathloss of aerial-terrestrial links. Besides, the mobility of UAV prompts us to consider the flight path of UAVs, i.e., trajectory planning, jointly with deployment issue to serve a time-varying IoT network. Moreover, several KPIs should be kept in mind when designing deployment schemes. First, high throughput is envisioned for terrestrial networks served by UAVs. Second, considering that onboard energy fundamentally limits the operational duration of UAVs, an energy-efficient deployment scheme along with a practical energy consumption model is vital for prolonging the network lifetime. Additionally, how to maximize the coverage availability while guaranteeing QoS requirements of each kind of IoT services is also an open issue.

C. INTERFERENCE MANAGEMENT

CR has been anticipated as one of promising technologies for SATINs towards IoT. Considering CCI is a major obstacle to achieve prospective advantages, interference management has been studied in satellite-terrestrial network as well as aerial-terrestrial network in terms of transmit beamforming or resource allocation. However, to increase the efficiency of spectrum reusing, it is necessary to guarantee the communication quality of primary networks when pursuing the communication performance of secondary networks. In other words, how to maximize the overall system performance through coordination and tradeoff of different network segments is the ultimate goal. Moreover, the distinct characteristics of the SATIN and IoT, such as the dispersion peculiarity of nodes, differences in node processing capabilities, limited load, and diverse IoT user requirements, impose new challenges on interference management to implement coexistence of these spectrum-sharing network segments. In this regard, it is hardly to eliminate interference through a single network segment, and how to conduct a cooperative interference management becomes the emphasis and difficulty. Other main challenges for interference management in SATINs towards IoT are analyzed as follows.

1) Energy-efficient communications:

Since both satellites, UAVs, and IoT devices are with limited onboard energy and inconvenient to be charged, it is significant to improve the spectrum efficiency of the IoT with an affordable power consumption. Moreover, considering the large numbers of connectivity demands in IoT, the satellite/aerial/terrestrial nodes consume significant energy to support CR operations. Therefore, energy-efficient

interference management is vital for system design of future environment-friendly cognitive SATINs.

2) Large-scale dispersion in 3D space:

In SATINs, terrestrial users, UAVs, and satellites distribute over a large-scale 3D space from the ground over air to space. The different horizontal positions and altitudes of nodes provide abundant spatial degree of freedom (DoF). In this situation, 3D beamforming along with accurate 3D channel model is an adequate approach for interference management. To utilize the spatial DoF sufficiently, more antennas would be employed, which increases the beamforming complexity in turn.

3) Low CSI feedback overhead:

When conducting resource management in such an integrated network with large number of antennas and IoT devices, downlink training and feedback overhead for acquisition of the channel state information (CSI) will exhaust the precious downlink resources. Thus, it is imperative to design a robust resource management scheme based on limited feedback CSI. In this regard, channel spatial correlations owing to large altitudes of satellites and UAVs can be exploited for CSI relaxation.

D. PHYSICAL LAYER SECURITY

For IoT applications like traffic monitoring, it is significant to avoid critical data being compromised and illegally used. However, due to the inherent characteristics of broadcasting and immense coverage, the cognitive SATIN network is vulnerable to malicious attacks [41]. Consequently, security has become a crucial design issue in the implementation and operation of SATINs especially when satellite/aerial network segments are employed for supporting IoT. Recently, physical layer security (PLS), which utilizes information theoretic and wireless channel characteristics to safeguard the confidential communications, has been receiving great research attentions in 5G networks. Without requiring secret keys and complex algorithms compared to traditional encryption techniques applied to upper layers, PLS is more suitable for the large-scale decentralized SATINs to facilitate global IoT.

To enhance the achievable secure rate, beamforming technology has been regarded as an efficient solution that exploits spatial DoF to improve the achievable rate of legitimate users while degrading that of eavesdroppers (Eves). However, employing beamforming for secure transmission in the SATIN is confronted with several key challenges. First, Eves are usually passive. Second, it is almost impossible to obtain the perfect CSI of any Eve, except for some location information at most. Besides, the wiretap environment is more challenging due to the 3D distribution of nodes. For example, when Eves (e.g., malicious UAVs) locate on the line between satellite and legitimate destinations (e.g., terrestrial IoT devices), it is difficult for satellite to distinguish the legitimate destinations with Eves from angle domain. In this case, artificial noise together with beamforming provides a new perspective for enhancing transmission security [42].
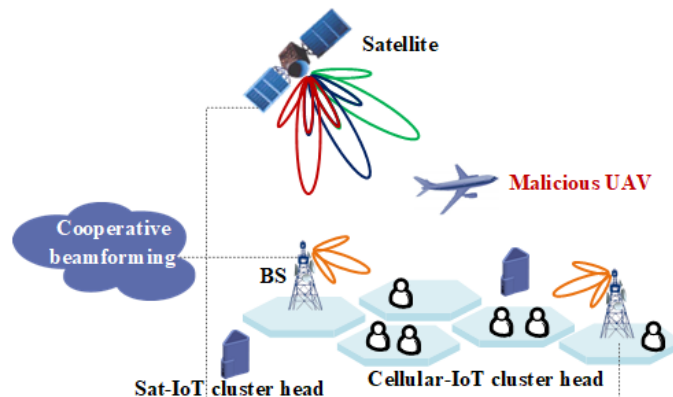
FIGURE 3. Cooperation of satellite and cellular networks for IoT communications with a malicious UAV.

In cognitive SATINs, single nodes or even single network segments can hardly cope with the aforementioned challenges due to limited computational capability and simplex resources. Alternatively, joint resource allocation, such as intra-segment virtual beamforming and inter-segment coordinated beamforming, can break through the performance upper bound achieved by a standalone equipment or network segment and contribute to secure and efficient IoT communications in cognitive SATINs.

V. CASE STUDY OF COOPERATIVE RESOURCE MANAGEMENT IN COGNITIVE SATINS FOR SECURE AND ENERGY-EFFICIENT IOT COMMUNICATIONS

In this section, we study a specific case to illustrate the advantages of conducting cooperative resource management in cognitive SATINs. To make the case study typical and general, we take the high-profile two-layer cognitive satellite-terrestrial network as an example, where satellite and terrestrial base stations (BSs) cooperate to serve IoT in the downlink scenario. Moreover, considering the openness of space channel and the imperfect management mechanism of aerial segment, we investigate a scenario where a non-collaborative and malicious UAV exists to verify the necessity and feasibility of cooperative resource management in an insecure communication environment.[1] In this cognitive satellite-terrestrial network with eavesdroppers, the cooperative resource management should be designed not only to combat the malicious UAV, but also to increase the communication performance of legitimate satellite users by eliminating the CCI between satellite and terrestrial networks introduced by cognitive radio. From this viewpoint, the considered scenario is a representative example to illustrate the

advantages of conducting cooperative resource management in cognitive SATINs, and can be easily extended to other general cases.

In the following, we firstly introduce the system model of the considered scenario. Then, we develop a joint beamforming scheme based on the cooperation of satellite and terrestrial BSs.[2] Finally, Simulation results are also given to verify the effectiveness of the proposed cooperative beamforming scheme.

A. SYSTEM MODEL

Fig. 3 shows a secure cognitive satellite-terrestrial network based IoT communication scenario, where a malicious UAV is attempting to wiretap the information from the satellite. The secondary satellite transmits signals to K satellite-IoT cluster heads reusing the frequency of primary BSs each serving one cellular-IoT cluster head. In this case, both satellite-IoT cluster-heads and cellular-IoT cluster heads suffer from inter-segment CCI and intra-segment CCI. The satellite and each BS carry M and N antennas, respectively. The UAV, satellite-IoT cluster heads, and cellular-IoT cluster heads are equipped with singular antenna.

To effectively counter the malicious UAV as well as the CCI caused by spectrum sharing, terrestrial BSs distributed within the satellite coverage operate as friendly jammers and conduct joint beamforming with the satellite. Moreover, considering that the malicious UAV and legitimate satellite-IoT cluster heads are distributed in a 3D space, the BSs adopt a 3D beamforming mechanism. Due to the different propagation environment, satellite downlinks usually contain line-of-sight (LoS) component while terrestrial links usually suffer from multipath fading. In this regard, we model the satellite downlink and terrestrial links as Ricean channel and Rayleigh channel, respectively.

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[1] We mainly focus on illustrating the advantages of conducting cooperative resource management in cognitive satellite-terrestrial networks and thus, the cooperative resource management proposed in this section is considered for a certain moment where the malicious UAV is assumed to be relatively static. For a long period where the UAV moves according to its 3D trajectory, the proposed cooperative resource management scheme is also feasible and we only need to update the solution of the resource allocation periodically.

[2]Cooperative beamforming between satellite and terrestrial BSs is supported by the SDN controller discussed in Section II.
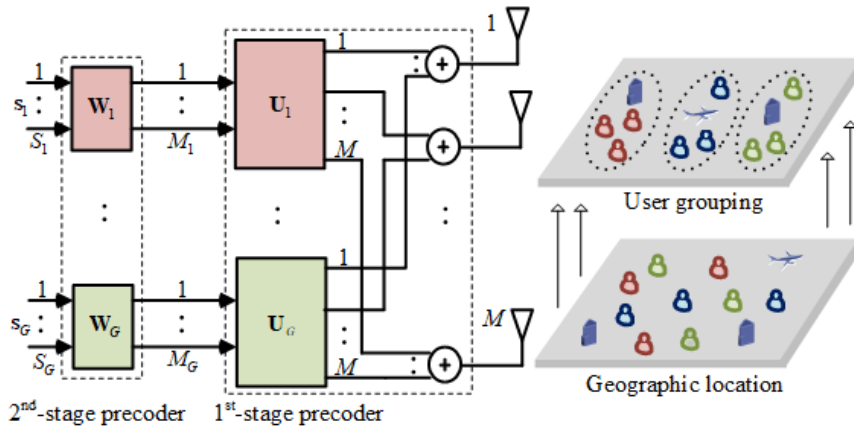
FIGURE 4. Framework of the JSDM based two-stage beamforming for satellite communications.

B. COOPERATION BASED SECURE AND ENERGY-EFFICIENT BEAMFORMING WITH LOW FEEDBACK

By exploiting the aforementioned characteristics of spatial correlations in SATINs, a joint spatial division and multiplexing (JSDM) based beamforming framework is employed at the satellite to reduce the channel training and CSI feedback overhead. As shown in Fig. 4, the key idea of JSDM lies in partitioning all receiving nodes into G groups with similar channel characteristics, and satellite serves each group with a two-stage downlink precoding scheme [43]. Specifically, the first-stage precoder $U_g \in C^{M \times M_g}$ $(g = 1, \cdots, G)$ is designed to eliminate inter-group interference semi-statically based on long-term CSI, i.e., second-order statistics of the channel, where M_g is the number of beams corresponding to the g-th group. In this article, U_g is generated through block diagonalization algorithm. The role of the pre-precoding is to reduce the dimensionality of the effective channel by exploiting the near-orthogonality of the eigenspaces of channel covariance matrices of different user groups. Next, with reduced dimensions on the effective channel, the second-stage dynamic precoder $W_g \in C^{M_g \times S_g}$ is designed to distinguish users within a group by suppressing intra-group interference, where S_g is the number of users scheduled in the g-th group. In the JSDM based beamforming framework, user grouping plays a decisive role in the efficiency of the interference cancellation. In this article, without any loss of generality, we take the K-means method, a machine learning based clustering algorithm, as an example to illustrate the user grouping schemes based on channel correlations.

Based on the JSDM beamforming framework, we then conduct joint optimization of the second-stage precoder W_g employed at the satellite and the 3D precoder V_j employed at the j-th BS, $j \in \mathcal{J} \triangleq \{1, \cdots, J\}$. Assuming one UAV Eve is wiretapping the i-th satellite-IoT cluster head ($SIoT_i$) in the g-th group, the achievable secure rate of the $SIoT_i$ can be given as $C_i (W_g, V) - C_e (W_g, V)$, where $C_i (W_g, V)$ is the achievable rate of the link between the satellite and $SIoT_i$,

and $C_e (W_g, V)$ is the achievable rate of the link between the satellite and the malicious UAV. Besides, in cognitive SATINs, energy efficient IoT communications is also significant due to the severe pathloss resulted from large communication distance in remote or emergency scenario. Taking both the requirements of energy efficiency and security of satellite communications into account, we formulate the joint beamforming scheme as an optimization problem with the objective of maximizing secrecy energy efficiency (sEE) of $SIoT_i$, which is defined as the ratio of the achievable secure rate to the total power consumptions. The optimization problem is formulated as

$$\max_{\substack{W_g, \forall g \\ V_j, \forall j}} \quad sEE_i = \frac{C_i (W_g, V) - C_e (W_g, V)}{\|W_{gi}\|^2 + P_0}$$

$$s.t. \quad C1 : C_j (W_g, V) \geq \Gamma_{th}^c \quad \forall j \in \mathcal{J}$$

$$C2 : \sum_{g,i} \|W_{gi}\|^2 \leq P_M \qquad (1)$$

where W_{gi} is the specific precoding vector for $SIoT_i$, P_0 is the circuit power consumed by the corresponding array flector of $SIoT_i$, and P_M is the maximum allowable transmit power of the satellite. C1 accounts for the rate constraint imposed by the primary cellular communications and Γ_{th}^c is the required rate threshold. We can employ the particle swarm optimization algorithm to solve this joint beamforming problem. From (1) we can see that, if we ignore the achievable rate of the link between the satellite and the malicious UAV, i.e., $C_e (W_g, V)$, the optimization problem can be easily degenerated to a general resource management problem in cooperative scenario.

C. PERFORMANCE EVALUATION

We conduct Monte Carlo simulations to validate the proposed cooperative beamforming scheme in the considered cognitive SATINs based IoT scenario. In the simulations, we set $M = 36$, $N = 8$, $K = 6$, $J = 2$, $G = 2$, $\Gamma_{th}^c = 3$ bits/s/Hz, $P_0 = 5$ W, and radius of cellular cell as 0.5 Km. We set the Ricean factor as 4 to fit the satellite
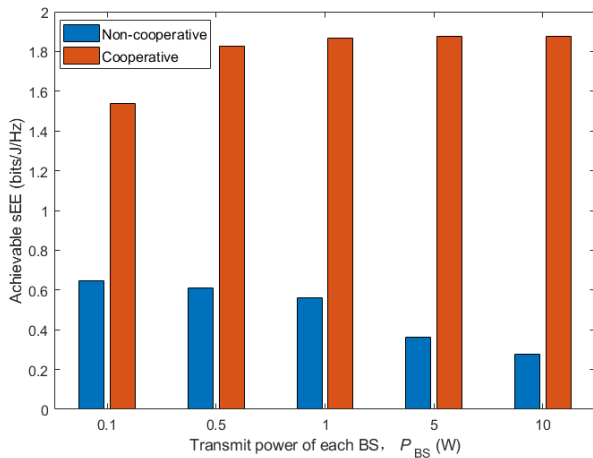
FIGURE 5. Comparison of sEEs with cooperative beamforming and non-cooperative beamforming ($P_M = 82$ W).

FIGURE 6. Achievable sEE versus the maximum transmit power of the satellite under different cooperative beamforming schemes.

link containing LoS component, with free space pathloss as 190 dB. Antenna gain at the satellite is 66.5 dBi, while antenna G/T of satellite-IoT cluster head is assumed as 16.9 dB/K in clear sky. The pathloss model for terrestrial links is $125 + 36\log_{10}(d)$ [d in Km].

To illustrate the benefits of employing inter-segment cooperation for IoT in cognitive SATINs, we compare the achievable sEEs of satellite-IoT cluster heads with cooperative beamforming and non-cooperative beamforming in Fig. 5. In non-cooperative case, only the beamforming vector W_g is optimized while V is implemented with zero-forcing algorithm under the given transmit powers. In cooperative case, the transmit power shown in x-axis is set as the maximum transmit power of each BS when conduct joint beamforming. As expected, through cooperation among different network segments, we can achieve higher sEE than that without cooperation. Moreover, as the transmit power of each BS increases, the achievable sEE of non-cooperative scheme deteriorates since severer CCI is imposed at the satellite-IoT cluster heads. On the contrary, the achievable sEE in the cooperative case gets larger as the transmit power of each BS increases, attributing to the fact that terrestrial BSs operate as friendly jammers and conduct joint beamforming with the satellite to counter the malicious UAV.

Fig. 6 depicts the achievable sEE versus the maximum allowable transmit power of the satellite under three cooperative beamforming schemes. The Ref. scheme refers to the secure rate maximized beamforming scheme as shown in [42]. As observed, the achievable sEE of the Ref. scheme increases at the beginning and deteriorates afterwards. This phenomenon accounts for the fact that the optimal transmit power keeps increasing to maximize the secure rate, and results in a lower sEE at its large region. Moreover, the proposed energy-efficient scheme is superior to the Ref. scheme and can obtain similar performance to the case without Eve, which verifies the effectiveness of the proposed scheme. Besides, as the maximum transmit power increases, the achievable sEE becomes saturated eventually. This is due
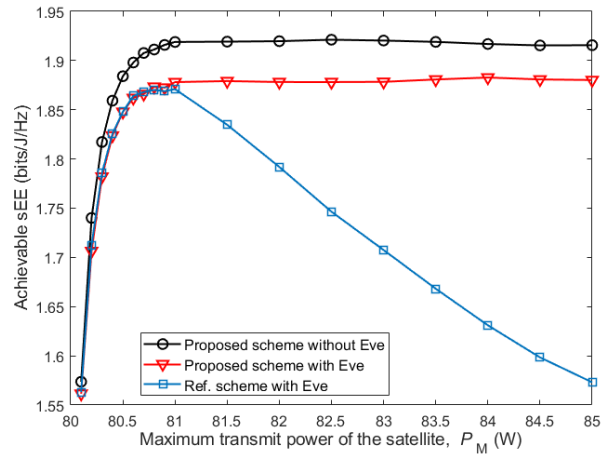
to the rate requirement limits the maximum feasible transmit power, although it is permitted by the transmit power constraint.

VI. CONCLUSION

In this paper, we have introduced a cognitive SATIN architecture with high throughput, cost-efficiency, and flexibility to facilitate the development of IoT. From the prospective of IoT characteristics and application requirements, main challenges for efficient resource management in terms of 3D spatial-temporal deployment of UAVs, interference management, and physical layer security have been analyzed. Moreover, we have proposed a cooperative beamforming scheme to enhance the security and energy efficiency of IoT communications in cognitive SATINs. Simulation results have verified the advantages of employing inter-segment cooperation and shown the effectiveness of the proposed resource management framework.

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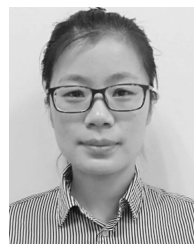
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