Cross-Tier Resource Allocation in Space-Air-Ground Integrated Networks for Internet of Remote Things

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Abstract

We present a new architecture of the 3D SAG wireless access networks for uplink communication between IoRT and LEO satellite, utilizing several multi-antenna UAV relays. The most important structural features of this network are as follows:

1) Due to the prominence of multi-antenna systems technology as a promising solution to achieve advanced telecommunication systems, multi-antenna UAV relays are considered in our system model. These relays have the capability to communicate with each other using singular value decomposition (SVD) beamforming technique.

2) To control the number of remote connections, only selected UAVs act as gateways to connect to the satellite.

3) The proposed architecture incorporates FSO space communication links to address limitations of the RF spectrum resource and achieve higher data rates for air-space links.

We formulate a new joint optimization problem of gateway selection, channel allocation, UAV deployment, and UAV power allocation for multi-tier communication in order to minimize the weighted sum of the number of gateways and the total UAV power consumption. Our proposed solution includes a two-step approach using constrained k-means clustering for channel allocation between IoRT devices and UAVs, and UAV location, and an algorithm inspired by simulated annealing (SA) for gateway selection, channel allocation between UAVs and gateways, and UAV transmit power optimization. The UAV power optimization is solved using the successive convex approximation (SCA) method.

Various simulations are performed to evaluate the performance of the proposed system model and the proposed optimization schemes. The results demonstrate the effectiveness of our proposed scheme in achieving optimal clustering, UAV deployment, and gateway selection. The required number of gateways for different scenarios is also determined. Notably, by implementing the SA algorithm to jointly optimize UAV transmit power, gateway selection, and UAV to gateway channel allocation, our proposed scheme achieves an average performance improvement of 48% compared to the case where only clustering is performed. The results also highlight the impact of the number of UAVs and the number of their antennas on the system performance.
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Abstract—In response to the increasing demands for high capacity and high data rates in space-air-ground integrated networks (SAGIN) as part of Internet of remote things (IoRT) networks, this paper proposes a system model and optimization scheme. The proposed architecture utilizes multi-antenna unmanned aerial vehicle (UAV) relays, with some of them being selected as gateways to transmit data to the satellite. The aerial links use radio frequency (RF) while the space links use free space optic (FSO). The optimization problem aims to minimize the weighted sum of the number of gateways and the total UAV power consumption by jointly optimizing UAV deployment, UAV power allocation, gateway selection, and channel allocation. By jointly adopting constrained k-means clustering, simulated annealing (SA) method, and successive convex approximation (SCA) method, a two-stage scheme is devised to solve the proposed NP-hard and non-convex problem. Our simulation results indicate that an average performance improvement of 48% is achieved by our proposed scheme compared to the case where only clustering is performed. Furthermore, the number of gateways required for Different scenarios is determined by the results. For instance, in order to minimize UAV power consumption without considering any constraint on the number of gateways, almost all UAVs are selected as gateways, and in this case, we achieve the highest data rate.

Index Terms—Space-Air-Ground network, RF/FSO, resource allocation, gateway selection, multi-UAV, multi-antenna UAV.

I. INTRODUCTION

In recent years, the rise of smart devices has brought attention to the Internet of things (IoT) technology. This technology has various applications, including providing internet connectivity for remote areas that lack terrestrial access networks, such as deserts, forests, and oceans. However, reliable connectivity in these areas, known as Internet of remote things (IoRT), faces challenges due to the absence of terrestrial access networks [1]. To solve this challenge, satellites are considered a complement to terrestrial networks [2], offering wide coverage, high service reliability, and continuous communication [3]. However, due to the long distance between satellites and terrestrial smart devices, direct connections are not possible for devices with insufficient power [4]. In response to this, the utilization of unmanned aerial vehicles (UAVs) in terrestrial-satellite networks and the development of a three-tier space-air-ground integrated network (SAGIN) have garnered significant interest from academia and industry, aiming to support diverse services in IoRT networks. Additionally, with the growing focus on the 6G network, the SAGIN has become a crucial research direction to meet the long-term requirements of comprehensive global 3D coverage and ubiquitous access [5]. The integration of different components in these networks is complex, and the dynamic nature of SAGIN further adds to the network’s complexity. Therefore, further research on cross-tier optimization and resource allocation in SAGIN is essential to achieve globally integrated network management [6]–[8].

In some papers, optical communication has been investigated in the development of the SAGIN infrastructure [9]–[10]. In [4] massive uplink connection is investigated for a satellite-aerial-terrestrial network (SATN), with the aid of a high-altitude platform station (HAPS); where data is transmitted from the terrestrial user to the HAPS using radio frequency (RF) links, and then the collected data is transmitted to the satellite using free space optic (FSO). The authors of [11] investigate the performance of both FSO and RF links in a satellite-UAV network to increase system throughput while reducing energy consumption. In [12], the effect of using a HAPS in a satellite-terrestrial system with hybrid RF/FSO communication links is shown, and analyses of the end-to-end average symbol error probability (SEP) and outage have been conducted. In addition, due to the importance of the location of the UAV in SAGIN performance, several researches such as [13]–[17] have been focused on finding the optimal UAV deployment. Resource allocation is also a key focus in enhancing system performance in many works. The optimization of HAPS deployment and resource allocation to maximize user throughput in SAGIN were investigated in [14]. In another study [15], an iterated algorithm combines two sub-problems to address energy efficiency and resource allocation in SAGIN with UAV relays. The same authors proposed a space-air-ground (SAG) wireless powered communication network in [16], assuming ground nodes transmit data using harvested energy from UAVs and jointly optimizing time slot division, subchannel allocation, power control, and UAV relay deployment to maximize system sum rate.

Among the research conducted on multi-UAV SAG networks, only some of them such as the ones in [17]–[20] have considered the communication capability between UAVs and discussed the selection of some UAVs as communication gateways with satellites. For example, [17] has investigated joint optimization of gateway selection, bandwidth allocation,
and UAV deployment to maximize spectral efficiency in the proposed SAGIN. Emphasizing the importance of gateway selection, the authors of [17] show that considering all UAVs as the relay node to satellite reduces the system spectral efficiency. Optimal gateway selection to minimize average link transmission energy is explored in [18]. Additionally, minimizing the number of gateways will reduce the cost of the computation [19].

In the literature mentioned above, the focus has been on single-antenna UAVs and the spatial multiplexing capability achieved by multi-antenna UAVs has been neglected. While the well-known advantages of using multiple antennas for UAVs with various beamforming technologies have the potential to significantly impact system performance. Although numerous papers have discussed the importance of this issue, including [7], [21]–[23], only a few have investigated multi-antenna UAVs in SAGIN. SAGIN communications with antenna array, beamforming and antenna array design, along with the related challenges have been examined in [7]. A 3D multiple input and multiple output (MIMO) UAV-satellite channel model based on regular geometry has been proposed in [24]. In [25], the UAV equipped with phased-array antennas amplifies satellite information by optimizing the detection vector. Then a max-min problem in terms of UAV energy efficiency is solved using a model of NOMA UAV-ground communication. Directing energy in the required directions is one of the crucial ways to save energy in wireless communication [26]. The UAV with directional antennas for energy minimization was examined in [27].

According to the stated various perspectives of SAGIN, we present a new architecture of three-tier networks in this research. By defining a new optimization problem, we take a step towards the improvement of SAGIN. Specifically, our main contributions can be summarized as follows:

- We present a new architecture of the 3D SAG wireless access networks for uplink communication between IoRT and LEO satellite, utilizing several multi-antenna UAV relays. The most important structural features of this network are as follows:
  1. Due to the prominence of multi-antenna systems technology as a promising solution to achieve advanced telecommunication systems, multi-antenna UAV relays are considered in our system model. These relays have the capability to communicate with each other using singular value decomposition (SVD) beamforming technique.
  2. To control the number of remote connections, only selected UAVs act as gateways to connect to the satellite.
  3. The proposed architecture incorporates FSO space communication links to address limitations of the RF spectrum resource and achieve higher data rates for air-space links.

- We formulate a new joint optimization problem of gateway selection, channel allocation, UAV deployment, and UAV power allocation for multi-tier communication in order to minimize the weighted sum of the number of gateways and the total UAV power consumption. Our proposed solution includes a two-step approach using constrained k-means clustering for channel allocation between IoRT devices and UAVs, and UAV location, and an algorithm inspired by simulated annealing (SA) for gateway selection, channel allocation between UAVs and gateways, and UAV transmit power optimization. The UAV power optimization is solved using the successive convex approximation (SCA) method.

- Various simulations are performed to evaluate the performance of the proposed system model and the proposed optimization schemes. The results demonstrate the effectiveness of our proposed scheme in achieving optimal clustering, UAV deployment, and gateway selection. The required number of gateways for different scenarios is also determined. Notably, by implementing the SA algorithm to jointly optimize UAV transmit power, gateway selection, and UAV to gateway channel allocation, our proposed scheme achieves an average performance improvement of 48% compared to the case where only clustering is performed. The results also highlight the impact of the number of UAVs and the number of their antennas on the system performance.

The rest of this paper is organized as follows. Section II, after stating the system model, introduces the channel model (space channels and Aerial channels), the communication model, and total UAV power consumption model. Section III formulates the cross-tier resource allocation problem of the desired network. Section IV describes the two-step suboptimal solution. Section V discusses our results. Finally, Section VI concludes this paper.

## II. System Model

In our model, we consider a 3D multi-UAV assisted network to implement a wireless access SAG-IoRT network. This network includes three tiers: space, air, and ground. There is a low earth orbit (LEO) satellite in the space tier, a set $U$ of $M$ UAVs each equipped with $M$ antenna in the air tier, and a set $K$ of $K$ single antenna terrestrial IoRT devices in the ground tier. Each UAV acts as a wireless relay node in this 3D environment and has the ability to communicate with satellite, IoRT devices, and other UAVs. In Fig. 1, we have shown an illustrative example of our model.

Here, we focus on the uplink communications from $K$ IoRT devices in a given remote area (with no cellular coverage), where the multiple UAVs act as the flying access points and gateways to relay the gathered data from IoRT devices to the LEO satellite. The LEO satellite height is $H_s$, and all UAV relays and IoRT devices are in the LEO satellite coverage. In our proposed 3D network, we assume that each UAV $u$ serves a set of $K_u$, where $\sum_{u \in U} K_u = K$, $\bigcap_{u \in U} K_u = \emptyset$, and $\text{card}(K_u) \leq M$, where $\text{card}()$ denotes the cardinality. These constraints indicate that the $U$ UAVs can cover all $K$ IoRT devices, but each IoRT device can only access to one UAV at a time.

The locations of the UAV $u$ and the IoRT device $k$ are indicated by $u, d_k$, respectively, where $u = (x_u, y_u, z_u)$,
where $d_k = (a_k, b_k, 0)$. We assume that the height of all UAVs are fixed at $H_u$. In our work, we use decode and forward (DF) relaying [28].

We consider that only some of the UAVs are selected as the gateways to collect the data from other UAVs and to relay these collected data to the satellite. Here, we define $\mathcal{G}$ as the selected set of $G$ UAVs as the gateways. Let’s $\gamma_u \in \{0, 1\}$ be a binary variable that is equal to 1 if UAV $u$ is selected as a gateway.

**A. Channel model**

In our model for 3D SAG wireless access networks, the wireless links are separated into two categories: space and aerial. The wireless space link is between the UAV gateway and the satellite (G2S). The wireless aerial link is between the UAV and the UAV gateway (U2G), as well as the connection between the IoT device and the UAV (D2U). Because of the low transmitting powers of IoT device and high path-loss between IoT devices and satellite, direct links between IoT devices and satellite are assumed to be unavailable [4].

1) **Space channels**: We use FSO for the G2S link due to the shortage of microwave spectrum resources, high satellite height and high data rate requirements at the G2S link. When an optical beam propagated into the atmosphere in FSO communication, it is affected by free-space path loss and channel fading [4]. So, the atmospheric channel state $h_{g}^{\text{FSO}}$ between UAV gateway $g$ and LEO satellite can be modeled as [29]

$$h_{g}^{\text{FSO}} = \sqrt{f_{g}^{\text{FSO}} f_{g}^{\text{FSO}}},$$

where $f_{g}^{\text{FSO}}$ is the path-loss of the FSO link between UAV gateway $g$ and LEO satellite, which is proportional to the transmitter and receiver gain, free space losses, atmospheric attenuation, FSO lenses losses [4]. In (1), $f_{g}^{\text{FSO}}$ is the channel fading coefficient between UAV gateway $g$ and LEO satellite. The above description is identical to the majority of the previous works on FSO communication [4] and [30]. Since in the FSO link, the $f_{g}^{\text{FSO}}$ is assumed to have a gamma-gamma distribution with pointing error, the probability density function (PDF) of $f_{g}^{\text{FSO}}$ can be expressed as follows in terms of Meijer G-function $G_{1,3}^{3,0}(.)$ using [31]

$$f_{f_{g}^{\text{FSO}}}(x) = \frac{\alpha \beta x^{2}}{\lambda_{0} \Gamma(a) \Gamma(a)} G_{1,3}^{3,0} \left( \frac{\alpha \beta x}{\lambda_{0}} \frac{\tau^{2}}{\tau^{2} - 1, \alpha - 1, \beta - 1} \right),$$

where $\alpha$ and $\beta$ are the effective numbers of large scale and small scale turbulence parameters of the scattering environment, respectively. $r$ describes the ratio between the equivalent beam radius and the pointing error displacement standard deviation, $\lambda_{0}$ is the pointing loss, and $\Gamma(.)$ is the gamma integral function [31].

2) **Aerial channels**: In our model, D2U and U2G communications use RF links, where path loss, shadowing, and multipath fading are the three propagation characteristics that are generally taken into account. Our system model incorporates all of the aforementioned impacts. So, the flat fading RF channel between IoT device $k$ and UAV $u$ and the channel gain between UAV $u$ and UAV gateway $g$ are represented by $h_{ku}^{\text{D2U}} \in \mathbb{C}^{M}$ and $h_{ug}^{\text{U2G}} \in \mathbb{C}^{M \times M}$, respectively, where $h_{ku}^{\text{D2U}} = h_{ku,m}^{\text{D2U}}$, $h_{ug}^{\text{U2G}} = h_{ug,m'm'}^{\text{U2G}}$ and $m, m' = 1, \ldots, M$, $m \neq m'$. $[.]_{mm'}$ denotes the $(m, m')$th element of the desired matrix. Here, $h_{ku}^{\text{D2U}}$, $h_{ug}^{\text{U2G}}$, are given by [14]

$$h_{ku}^{\text{D2U}} = \left( \frac{c}{4 \pi f_{c} d_{ku}^{\text{D2U}}} \right) \left( \frac{1}{A(d_{ku}^{\text{D2U}})} \right) F_{ku,m'},$$

$$h_{ug}^{\text{U2G}} = \left( \frac{c}{4 \pi f_{c} d_{ug}^{\text{U2G}}} \right) \left( \frac{1}{A(d_{ug}^{\text{U2G}})} \right) F_{ug,m'm'},$$

Propagation path loss are covered by the first factor in (3) and (4), where $c$ and $f_{c}$ are the speed of light and carrier frequency, respectively. The distance between IoT device $k$ and UAV $u$ is $d_{ku}^{\text{D2U}}$, while the distance between UAV $u$ and UAV gateway $g$ is $d_{ug}^{\text{U2G}}$. $F_{ku,m'}$ represents the fading channel between the IoT device $k$ and the antenna $m$ of the UAV relay $u$. This fading channel is characterized by a Rician fading distribution with Rician factor $K_{R\text{D2U}}$ [32]. Also, there is a line of sight (LoS) link for the U2G channel due to UAV height in general [17]. Therefore, the fading channel between the antenna $m'$ of UAV $u$ and the antenna $m$ of UAV gateway $g$ has a Rician distribution with Rician factor $K_{U\text{2G}}$. $A(d_{ku}^{\text{D2U}})$ and $A(d_{ug}^{\text{U2G}})$ are the attenuation gains due to clouds and rain. This gain model over the first 3 km of height is the same as the one used in [33] and [34], which are affected by the distance between the IoT device and UAV relay in D2U link and distance between two UAVs in U2G link, respectively. These are given as follows:
3d_{D2U}^{	ext{U}}\chi
\begin{align*}
A(d_{k_u}^{\text{D2U}}) &= 10 - 10\log_10 H_u, \\
A(d_{ug}^{\text{U2G}}) &= 10 - 10\log_10 H_g,
\end{align*}
where $\chi$ is the attenuation factor (in dB/km) caused by clouds and rain.

\section*{B. Communication model}

In our proposed system, the data from the IoRT devices should be collected by UAVs using D2U links, then U2G links are used to transmit the gathered data to the gateways, and the UAV gateways finally relay this data to the satellite via G2S links. For simplicity, we assume that each tier operates in a different frequency band and there is no interference between the different tiers. Let $B_{RF}$ define the microwave allocated bandwidth which is divided equally and orthogonally among the different layers, and let $B_{GSO}$ define the optical allocated bandwidth for the G2S link.

Additionally, in order to reduce the problem of intra-tier interference, we equally divide the frequency band resources used by each tier into $U$ sub-channels. So, each UAV in each tier operates in a different frequency sub-channel without interfering with the others.

The channel allocation matrix between IoRT devices and UAV relays is defined as $A^{\text{D2U}} \in \mathbb{C}^{K \times U}$, where $[A^{\text{D2U}}]_{k, u} = a^{\text{D2U}}_{k, u}$, $a^{\text{D2U}}_{k, u} = 1$ if the IoRT device $k$ is connected to the UAV $u$, otherwise, $a^{\text{D2U}}_{k, u} = 0$. And the channel selection matrix between the UAVs and the UAV gateways is defined as $A^{\text{U2G}} \in \mathbb{C}^{U \times U}$, where $[A^{\text{U2G}}]_{u, u'} = a^{\text{U2G}}_{u, u'}$. Similarly, $a^{\text{U2G}}_{u, u'} = 0$ denotes the absence of a direct link of communication between the UAV $u$ and the UAV gateway $u'$.

The received signal $y_u \in \mathbb{C}^M$ at the UAV relay $u$ from IoRT devices can be expressed as

$$
y_u = \sum_{k \in K_u} \sqrt{p^{\text{D2U}}_k} h_{k u}^{\text{D2U}} x_k + n_u, \quad n_u \sim CN(0, \sigma_n^2 I_M),
$$

where $p^{\text{D2U}}_k \geq 0$ denotes the transmission power of the IoRT device $k$, $h_{k u}^{\text{D2U}} \in \mathbb{C}^M$ denotes the channel vector between IoRT device $k$ and the UAV $u$, $x_k$ is the symbol transmitted by IoRT device $k$, $n_u$ is the additive white Gaussian noise (AWGN) at the UAV $u$ and $I_M$ is the $M \times M$ identity matrix. In particular, we assume that uplink data detection is performed via linear processing. We consider maximum ratio combining (MRC) for detection because, in the low signal to noise ratio (SNR) region, MRC performs better than zero forcing (ZF) and has low complexity [35]. Also, we assume that the UAVs are able to acquire perfect channel state information (CSI). We use $c_{k u}$ as the linear combining vector assigned to the IoRT device $k$ for UAV $u$, which gives $c_{k u} = h_{k u}^{\text{D2U}}$. So, UAV $u$ applies a linear combining matrix $C_{u} = \{c_{k u} | a_{k u}^{\text{D2U}} = 1, k \in K\} \in \mathbb{C}^{\text{card}(K_u) \times M}$ to the received signal, as $C_{u}^{H} y_u$, where $(\cdot)^H$ denotes the conjugate transpose.

Therefore, based on the received signal at the UAV $u$ from IoRT devices, the instantaneous signal-to-interference-plus-noise-ratio (SINR) expression for the IoRT device $k \in K_u$ to the UAV $u$ is given by [36]

$$
\text{SINR}_{k_u}^{\text{D2U}} = \frac{p^{\text{D2U}}_k |c_{k u}^H h_{k u}^{\text{D2U}}|^2}{\sum_{k' \in K_u \setminus k} p^{\text{D2U}}_{k'} |c_{k u}^H h_{k u}^{\text{D2U}}|^2 + \sigma_n^2 \|c_{k u}\|^2}.
$$

And the uplink achievable data rate from IoRT device $k \in K_u$ to UAV $u$ is given as [36]

$$
R_{k_u}^{\text{D2U}} = B_s \log_2 (1 + \text{SINR}_{k_u}^{\text{D2U}}),
$$

where $B_s$ denotes the bandwidth allocated to the D2U links for each UAV. After detecting the signal at the corresponding UAV, symbol vector $\hat{x}_u \in \mathbb{C}^{\text{card}(K_u)}$ is regenerated and forwarded to a UAV gateway via single-hop U2G wireless link. Hence, each UAV sends its data directly to one of the UAV gateways using SVD beamforming.

Here, we assume CSI is available at both transmitter and receiver, and the SVD of the MIMO channels is used to obtain the beamforming vectors at the transmitter and receiver. The SVD of the channel is denoted by [37]

$$
H_{u g}^{\text{U2G}} = U_{u g}^{\text{U2G}} \Lambda_{u g}^{\text{U2G}} V_{u g}^{\text{U2G}}^H,
$$

where $U_{u g}^{\text{U2G}} \in \mathbb{C}^{M \times M}$ and $V_{u g}^{\text{U2G}} \in \mathbb{C}^{M \times M}$ are the two unitary matrices, and $\Lambda_{u g}^{\text{U2G}} = \text{diag}(\Lambda_{u g,1} \Lambda_{u g,2} \cdots \Lambda_{u g,M})$ is the $M \times M$ diagonal matrix having non-negative real values, i.e., the singular values are $\Lambda_{u g,1} \geq \lambda_{u g,2} \geq \cdots \geq \lambda_{u g,M} \geq 0$.

We assume that card($K_u$) ≤ rank$(H_{u g}^{\text{U2G}})$. The UAV, after applying the suitable power factor, multiplies $\hat{x}_u$ by $V_{u g}^{\text{U2G}} \in \mathbb{C}^{M \times \text{card}(K_u)}$ before sending through its antennas. In the other side, UAV gateway multiplies the received signal by the matrix $\hat{U}_{u g}^{\text{U2G}} \in \mathbb{C}^{\text{card}(K_u) \times M}$, and $\hat{V}_{u g}^{\text{U2G}}$ and $\hat{U}_{u g}^{\text{U2G}}$ contain the first card($K_u$) columns of $V_{u g}^{\text{U2G}}$ and $U_{u g}^{\text{U2G}}$, respectively. As a result, the MIMO channel is converted into rank($H_{u g}^{\text{U2G}}$) independent, orthogonal, and parallel SISO subchannels using SVD [37]. Also, due to the increase in the total achievable data rate of system, we make the assumption that among IoRT devices connected to a UAV, the subchannel $i$ with the larger $\Lambda_{u g, i}$, where $i = 1, \ldots, \text{card}(K_u)$, is assigned to the device with the larger $R_{k_u}^{\text{D2U}}$. Therefore, the receiving SNR expression for IoRT device $k \in K_u$ at the output of Rx beamformer is

$$
\text{SNR}_{u g, k}^{\text{U2G}} = \frac{p_{u g, k}^{\text{U2G}} |\Lambda_{u g, i}^{\text{U2G}}|^2}{\sigma_n^2},
$$

where $\sigma_n^2$ denotes the noise power at the UAV gateway $g$, and $p_{u g, i}^{\text{U2G}}$ indicates the transmit power of subchannel $i$ of the UAV $u$ and we have $\sum_{i = 1}^{\text{card}(K_u)} p_{u g, i}^{\text{U2G}} = p_{u g}^{\text{U2G}}$, which represents the transmitted power of the RF link from the UAV $u$. For simplicity we allocate equal power to each subchannel thus $p_{u g, i}^{\text{U2G}} = \frac{p_{u g}^{\text{U2G}}}{\text{card}(K_u)}$.

The uplink achievable data rate of IoRT device $k \in K_u$ from UAV $u$ to UAV gateway $g$ is
\[ R_{U2G}^{U2G} = B_s \log_2(1 + SNR_{U2G}^{U2G}), \]

where \( B_s \) denotes the bandwidth allocated to the U2G links for each UAV. After Rx beamforming over the received signal at the UAV gateway, the symbol of each IoRT device is forwarded to the LEO satellite. We use frequency-division multiple access (FDMA) techniques, due to the large bandwidth that we have in the FSO link. We define \( K_g \) as the set of IoRT devices that are connected to UAV gateway \( g \), where \( \text{card}(K_g) = \text{card}(K_g) + \sum_{u=1}^{U} \text{card}(K_u) d_{U2G}^{U2G} \). So, the received SNR expression for each IoRT device \( k \in K_g \) at the LEO satellite from the UAV gateway \( g \) over FSO link is given by

\[ \text{SNR}_{G2S}^{G2S} = \frac{p_{1}^{FSO} \eta_s G_{s}^{G2S} G_{s}^{FSO} |b_{1}^{FSO}|^2}{\sigma_s^2}, \]

where \( p_{1}^{FSO} \geq 0 \) denotes the transmit power of FSO link at UAV gateway \( g \), \( \eta_s \) indicates the optical-to-electrical conversion efficiency, the transmit telescope gain at the UAV gateway is indicated by \( G_{s}^{G2S} \), the receive telescope gain at LEO satellite is indicated by \( G_{t}^{FSO} \), \( B_s \in \mathbb{C} \) denotes the channel between the UAV gateway \( g \) and the LEO satellite, and \( \sigma_s^2 \) represents the noise power at the LEO satellite. This is a frequently of optical wireless system [38].

Similarly, the uplink achievable data rate for the G2S link from UAV gateway \( g \) to the LEO satellite for FSO link is given by

\[ R_{G2S}^{G2S} = \frac{B_s}{\text{card}(K_g)} \log_2(1 + \text{SNR}_{G2S}^{G2S}), \]

where \( B_s \) stands for the bandwidth allocated to the G2S communication for each gateway.

As a result, the uplink achievable data rate for IoRT device \( k \) to LEO satellite, \( R_k \), and the total achievable data rate of system, \( R_{\text{total}} \), are respectively expressed as

\[ R_k = \begin{cases} \forall k \in K_g, \forall u \in G : \\
\min \{ \sum_{u=1}^{U} R_{D2U}^{D2U} d_{ku}^{D2U}, \\
\sum_{u=1}^{U} p_{FSO} |b_{FSO}|^2 d_{ku}^{D2U} \}, \\
\forall k \in K_g, \forall u \in U - G : \\
\min \{ \sum_{u=1}^{U} R_{D2U}^{D2U} d_{ku}^{D2U}, \\
\sum_{u=1}^{U} \sum_{u=1}^{U} R_{U2G}^{U2G} d_{ku}^{U2G} d_{ku}^{U2G} \}, \\
\sum_{u=1}^{U} \sum_{u=1}^{U} R_{G2S}^{G2S} d_{ku}^{G2S} d_{ku}^{G2S} \}, \\
\end{cases} \]

and

\[ R_{\text{total}} = \sum_{k=1}^{K} R_k. \]

C. Total UAV power consumption

Optimizing the UAV power consumption model is indeed necessary to maximize the service time, as the UAV system cannot replenish electrical power or propellant fuel while in flight.

The UAV power consumption comprises two types of power, i.e., UAV transmission power and UAV circuit power.

Since the power consumption of the laser is negligible, it is omitted and the UAV circuit power only includes the power of the RF chain circuits [39]. The UAV transmission power can be the transmission power of RF link or FSO link, depending on whether the UAV is acting as a gateway or not. As a result, the total UAV power consumption can be modeled as follows:

\[ P_{U2G} = \sum_{g=1}^{U} \sum_{u=1}^{U} p_{U2G}^{U2G} d_{u2g} + \sum_{g=1}^{U} p_{G}^{G} \gamma_g \]

total UAV transmission power \( (P_{U2G}) \)

\[ + \sum_{g=1}^{U} M_{FR}(U - \sum_{g=1}^{U} \gamma_g) \]

total UAV circuit power \( (P_{c}) \)

The RF chain circuit power \( p_{RF} \) is kept constant for simplicity of analysis.

III. PROBLEM FORMULATION

In this section, we formulate the cross-tier resource allocation problem in 3D SAG wireless access networks for communication between internet of remote things and LEO satellite.

The multi-objective function is the weighted sum of the number of gateways and total UAV power consumption. It’s important to note that these metrics must be normalized with respect to their maximum values to make them comparable, as they have different values and units.

We further introduce a binary variable \( \alpha \in [0, 1] \) to distinguish between considering only the transmitted power of the UAV \( (\alpha = 0) \) or the total power consumption of the UAV \( (\alpha = 1) \), which includes both the UAV transmission power and UAV circuit power. As a result, we model the multi-objective function as follows:

\[ \omega \frac{\sum_{u=1}^{U} \gamma_u}{U} + (1 - \omega) \frac{P_{U2G}^{\text{max}} + \alpha P_{c}^{\text{max}}}{P_{U2G}^{\text{max}}}, \]

where \( \omega \in [0, 1] \) is weighting factor that combines the multi-objective function into one value, and represents the relative importance of the considered metrics. By adjusting the value of \( \omega \), we can dynamically control the preference between the number of gateways and power of UAVs. For instance, if the UAV’s battery is running low, the value of \( \omega \) should be reduced to prioritize saving power. While in some cases when connecting to the satellite is costly, we could increase the value of \( \omega \). In (18), the maximum number of gateways is equal to the number of UAVs, and \( P_{U2G}^{\text{max}} \) occurs when one of the UAVs is a gateway, and it is defined as follows:

\[ p_{U2G}^{\text{max}} = p_{U2G}^{\text{max}}(U - 1) + p_{G}^{G} \gamma_g \]

where \( p_{U2G}^{\text{max}} \) and \( p_{G}^{G} \gamma_g \) are maximum transmission power of each UAV in RF and FSO links, respectively. We minimize this multi-objective function by jointly optimizing the gateway selection, channel allocation, UAV location deployment, and UAV power allocation. Let’s \( \Gamma \) denote the set of gateway
selection as $\Gamma = \{y_u\}$, the set of channel selection matrix as $A = [A^{D2U}, A^{U2G}]$, the set of UAV location $D = \{u_u\}$, and the set of transmission power of UAV relays as $P_u = \{p_{U}^{U2G}, p_{FSO}^{U2G}\}, \forall u \in U - G$ and $V_g \in \mathcal{G}$. So, the cross-tier resource allocation problem can be formulated as

$$
\begin{align}
\min_{\omega, \mathbf{A}, \mathbf{P}_u} & \quad \omega \mathbf{1}_\text{normalize} + (1 - \omega) P_\text{UAV} \\
\text{s.t.} & \quad 0 \leq p_{U}^{U2G} \leq p_{U}^{\text{max}} , \forall u \in U - G, \quad (20b) \\
& \quad 0 \leq p_{FSO}^{U2G} \leq p_{FSO}^{\text{max}} , \forall u \in U, \quad (20c) \\
& \quad \text{card}(\mathcal{K}_u) \leq M , \forall u \in U, \quad (20d) \\
& \quad r_{ku}^{\text{min}} \leq \sum_{u=1}^{U} R_{k, u}^{\text{D2U}} a_{ku}^{\text{D2U}} , \forall k \in \mathcal{K}, \quad (20e) \\
& \quad r_{ku}^{\text{min}} \leq \sum_{u=1}^{U} R_{k, u}^{\text{U2G}} a_{kg}^{\text{U2G}} , \forall k \in \mathcal{K}, \quad (20f) \\
& \quad \sum_{k \in \mathcal{K}_u} R_{k, u}^{\text{D2U}} \leq \sum_{g=1}^{G} \sum_{u=1}^{U} R_{u, g}^{\text{U2G}} a_{gu}^{\text{U2G}} , \forall u \in U - G, \quad (20g) \\
& \quad \sum_{k \in \mathcal{K}_u} R_{k, u}^{\text{D2U}} + \sum_{u=1}^{U} \sum_{k \in \mathcal{K}_u} R_{u, g}^{\text{U2G}} a_{gu}^{\text{U2G}} \leq \text{card}(\mathcal{K}_G) R_{g, k}^{\text{G2S}} , \forall g \in \mathcal{G}, \quad (20h) \\
& \quad \sum_{u=1}^{U} a_{ku}^{\text{D2U}} = 1 , \forall k \in \mathcal{K}, \quad (20i) \\
& \quad \sum_{u=1}^{U} a_{ku}^{\text{U2G}} = 1 , \forall u \in \mathcal{U} - G, \quad (20j) \\
& \quad \sum_{u=1}^{U} y_u \geq 1 , \forall u \in \mathcal{U}, \quad (20k) \\
& \quad y_u \in [0, 1] , \forall u \in \mathcal{U}, \quad (20l) \\
& \quad \sum_{k \in \mathcal{K}_u} r_{ku}^{\text{D2U}} \in [0, 1] , \forall u \in \mathcal{U}, \forall k \in \mathcal{K}, \quad (20m) \\
& \quad \sum_{u=1}^{U} a_{ku}^{\text{U2G}} \in [0, 1] , \forall u \in \mathcal{U}, \forall u' \in \mathcal{U}, \quad (20n)
\end{align}
$$

where constraints (20b) and (20c) guarantee that the transmit power of each UAV is non-negative and does not exceed the maximum transmission power limit for both RF and FSO links, (20d) guarantees that the number of IoRT devices connected to each UAV should not exceed the number of UAV antennas, (20e)-(20g) guarantee that each IoRT device data rate, $R$, meets its minimum rate requirement, denoted as $r_{ku}^{\text{min}}$, constraints (20h) and (20i) satisfy the flow conservation constraints in a multi-hop network, which states that the sum of data flows entering each UAV must be lower than or equal to its total outgoing data flows [40]. constraint (20j) guarantees that each IoRT device is connected to at most one UAV relay and (20k) allows each UAV to directly transmit data to at most one of the gateways. constraint (20l) indicates that at least one of the UAVs must be selected as a gateway for connection to the satellite.

As it is seen, the problem (20) is mixed-integer nonlinear programing (MINLP), and is generally NP-hard [41] as it contains integer variables and non-linear constraints. We propose an efficient heuristic solution with reasonable computational complexity, which is described in Section IV.

IV. PROPOSED THREE-STEP SOLUTION

We suggest a low-complexity and two-step suboptimal solution. Hence, the problem (20) is divided into two subproblems. In the first subproblem, according to the distribution of IoRT devices, channel allocation between IoRT devices and UAVs is carried out via clustering, and the optimal location of the UAVs is also determined. Then, based on the result of the first subproblem, the UAV gateways, the channel allocation of UAVs and UAV gateways, and the optimized power of the UAVs are determined in the second subproblem.

A. D2U channel allocation and UAV deployment optimization

The D2U channel model suggests that the shorter distance between the IoRT device and the UAV results in a higher average received SNR, leading to a higher data rate in the network. Based on this, we employ the constrained k-means clustering algorithm [42], taking into account constraints (20d), (20e), (20f), to allocate channels between IoRT devices and UAVs. The UAVs are then positioned at the center of each cluster.

Therefore, the constrained k-means clustering algorithm is performed according to the distribution of devices on the ground. So, typically, devices in close proximity are grouped together in the same cluster, and the number of clusters corresponds to the number of available UAVs.

To satisfy the constraint (20d), before joining a cluster, an IoRT device checks the number of members in the desired cluster. If the number of members equals the number of UAV antennas, the new IoRT device is placed in another cluster with the closest centroid, in which the number of members is less than the number of UAV antennas.

The initial starting point of the k-means algorithm is chosen randomly. So, the initial centroids of the clusters are selected randomly from the locations of the IoRT devices based on the required number of clusters. If the QoS constraint (20e) is not met, the algorithm is executed with a different initial starting point until the constraint is satisfied. If the constraint is still not satisfied after 100 iterations, an additional UAV is added, and clustering is performed.

After these steps, the $A^{D2U}$ channel allocation matrix is determined based on the clustering algorithm, and the IoRT devices in each cluster are connected to the UAV located at the centroid of that cluster. These steps are outlined in Algorithm 1.

B. Joint UAV power optimization, gateway selection and U2G channel allocation

In the second subproblem, based on the results of the previous subproblem, we determine the UAVs that will act
as gateways to communicate with the satellite. We also decide which gateway each remaining UAV will connect to. Also, we solve the UAV power optimization problem given the UAV deployment position, gateway selection, and channel allocation.

1) **UAV power optimization**: The UAV power optimization of problem (20) can be written as

$$\min_{\{P_u\}} P_{UAV}^t, \quad (21)$$

s.t. (20b), (20c), (20f) −(20i).

The first term of the objective function of the optimization problem (20a) as well as $P_{UAV}^t$ are removed from the objective function of the UAV power optimization problem (21) because they are not a function of $P_u$. Due to the nonconvexity of the constraint (20i), problem (21) is nonconvex and cannot be solved by convex optimization methods. In order to solve it, we use the SCA method to handle the nonconvex constraint (20i) and approximate the original function with a convex function in each iteration at a given local point [43].

Since the first-order Taylor expansion of a concave function is a global upper bound of its function value at every point [44], the nonconvex term in constraint (20i) is replaced by its convex upper bound, $R_{Ug,k}$, with a given low point in each iteration. It means that we have

$$R_{Ug,k} = B_u \log_2(1 + \frac{P_{Ug}^n}{\sigma_g^2} (\lambda_{Ug,k})^2) \leq R_{Ug,k}^{\text{new}}. \quad (22)$$

With given point $P_{Ug}^n$ in the iteration n, the first-order Taylor expansion of $R_{Ug,k}^{\text{new}}$ is given by

$$R_{Ug,k}^{\text{new}} = B_u [\log_2(1 + \frac{P_{Ug}^n}{\text{card}(K_g)} (\lambda_{Ug,k})^2)] + \frac{(\frac{P_{Ug}^n}{\text{card}(K_g)} - \lambda_{Ug,k})(\lambda_{Ug,k}^2)}{\ln(2)(\sigma_g^2 + \frac{P_{Ug}^n}{\text{card}(K_g)} (\lambda_{Ug,k})^2)}. \quad (23)$$

So, the constraint (20i) will be transformed into a convex constrain and the UAV power optimization problem can be rewritten as

$$\min_{\{P_u\}} P_{UAV}^t, \quad (24a)$$

s.t. $\sum_{k \in K_g} R_{Ug,k}^{\text{new}} + \sum_{u=1}^{U} \sum_{k \in K_g} R_{Ug,k}^{\text{new}} d_{Ug} \leq (\text{card}(K_g)) P_{Ug}^n G_{s,k}, \quad \forall g \in G, \quad (24b)$

(20b), (20c), (20f) − (20i).

Since the objective function of problem (24) is linear and its related constraints are convex, (24) is a convex optimization problem, which can thus be solved optimally by CVX toolbox and SeDuMi solver.

2) **SA algorithm**: As a result, for any given UAV deployment position, and D2U channel allocation, optimization problem (20) can be transformed as

$$\min_{\{\Gamma, A_{Ug}, P_u\}} \omega \Gamma_{\text{normalize}} + (1 - \omega) P_{UAV}^t \quad (25)$$

s.t. (20b), (20c), (20f) − (20i), (20k) − (20m), (20o).

The exhaustive search can be used to find the optimal gateways among UAVs, but it has a large overhead on the system due to the high computational complexity. To address this, we are inspired by the SA algorithm [45], a meta-heuristic method widely used in optimization problems, notably for avoiding local minima [46]. Based on the U2G channel model, connecting UAVs to the closest gateway consumes less power when there is no constraint.

The details of the joint UAV power optimization, gateway selection, and U2G channel allocation algorithm inspired by the SA algorithm are summarized in Algorithm 2.

To create a neighbor solution $\Gamma_{\text{new}}$ in Algorithm 2, a UAV is randomly selected, and its state in the current iteration is set to the opposite of its state in the previous iteration, that means, if it was selected as a gateway in the previous iteration, it will not be selected as a gateway in the current iteration, and conversely [17]. The states of the remaining UAVs remain identical to those from the previous iteration. By implementing Algorithm 2, we can achieve a near-optimal decision for gateway selection and U2G channel allocation.

If the QoS constraints in the sixth line of Algorithm 2 is not satisfied after 100 iterations, we create another random value for $\Gamma$ and continue the Algorithm 2.

Based on [47], the computational complexity of (24) is $O \left( \bar{n} \bar{m}^{2.5} + \bar{m}^{2.5} \right)$, where $\bar{n} = U$ and $\bar{m} = 2(U + K)$ are the number of decision variables, and the number of constraints, respectively. Since step 17 in Algorithm 2 (related to solving the convex power optimization problem (24)) has the most computational complexity, the calculation complexity of Algorithm 2 is $O \left( \text{MaxIter}_\text{max} \left( \frac{\bar{n} \bar{m}^{2.5}}{\bar{m}^{2.5}} \right) \right)$. MaxIter is number of repetitions of the while loop.

V. SIMULATION RESULTS AND DISCUSSION

In this section, we evaluate the performance of the proposed approaches for the SAG-IoRT network. In our simulations, we consider that IoRT devices are uniformly distributed in the area
Algorithm 2 Joint UAV power optimization, gateway selection and U2G channel allocation algorithm

Input: $d_i$, $A^{U2Us}$, $u_i^*$, $T_0$, $T_{\text{final}}$, $t_{\text{max}}$, $\delta$.
Output: $\Gamma^*$, $A^{U2Gs}$, $P^*_U$.

1: Initialize: Set the temperature to $T = T_0$. Generate a random values for $\Gamma$ according to constraints (20l) and (20m). Compute the objective function of problem (25), $\text{func}(\Gamma, A^{U2G}, P^*_U)$.
2: while $T \geq T_{\text{final}}$ do
3: for $t = 1$ to $t_{\text{max}}$ do
4: Generate a neighbor solution $\Gamma^{\text{new}}$ according to constraints (20l) and (20m).
5: Connect UAVs that are not connected to the satellite to the nearest gateway, and calculate $A^{U2G,\text{new}}$.
6: if constraints (20f)-(20i) are not satisfied then
7: Go to Step 4.
8: else
9: solve the UAV power optimization problem (24), $P_{\text{new}}^U$.
10: Calculate the objective function of problem (25), $\text{func}(\Gamma^{\text{new}}, A^{U2G,\text{new}}, P_{\text{new}}^U)$.
11: end if
12: $\Delta = \frac{\text{func}(\Gamma^{\text{new}}, A^{U2G,\text{new}}, P_{\text{new}}^U)}{\text{func}(\Gamma, A^{U2G}, P^*_U)}$.
13: generate a random number $\eta_{\text{rand}} \in (0, 1)$.
14: if $\Delta \leq 0$ or $e^{\frac{T}{\delta}} > \eta_{\text{rand}}$ then
15: $\Gamma^* = \Gamma^{\text{new}}$, $A^{U2G*} = A^{U2G,\text{new}}$, $P^*_U = P_{\text{new}}^U$.
16: end if
17: end for
18: $T = \delta T$.
19: end while

Fig. 2: Illustration of the clustering, UAV deployment, and gateway selection given distribution of IoRT devices.

of size 1 km $\times$ 1 km. For all simulations, 20 IoRT devices, and 6 UAV relays with 4 antennas are considered, unless otherwise noted. The presented simulation results are averaged over 1000 different configurations. The AWGN power spectrum density in RF is $-174$ dBm/Hz and in FSO is $-143,83$ dB/Hz $\cdot$ The parameters used in the simulations are summarized in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_e$</td>
<td>500 km</td>
<td>$H_u$</td>
<td>300 m</td>
</tr>
<tr>
<td>$B_{RF}$</td>
<td>100 MHz</td>
<td>$B_{FSO}$</td>
<td>30 GHz</td>
</tr>
<tr>
<td>$r_{\text{min}}$</td>
<td>10 Kbps</td>
<td>$P_{\text{PSO}}$</td>
<td>0.1 watt</td>
</tr>
<tr>
<td>$p_{\text{max}}$</td>
<td>0.5 watt</td>
<td>$P_{\text{PSO}}$</td>
<td>15 dBm</td>
</tr>
<tr>
<td>$p^*_U$</td>
<td>0.25 watt</td>
<td>$P_{\text{PSO}}$</td>
<td>$-72$ dB</td>
</tr>
<tr>
<td>$K^{D2U, U2G}$</td>
<td>10</td>
<td>$G_{FSO}$</td>
<td>1</td>
</tr>
<tr>
<td>$G_{FSO}$</td>
<td>$f_c$</td>
<td>2.902</td>
<td>$A_0$</td>
</tr>
</tbody>
</table>

Fig. 2 illustrates the distribution of IoT devices, their clustering, and the optimal deployment of UAVs as well as selected gateways following our proposed framework. Our solution considers the given distribution of IoT devices and their clustering to determine the best positions for the UAVs. Additionally, for the defined problem with $\omega = 0.6$ and $\alpha = 1$, our solution selects two gateways from these UAVs to establish communication with the satellite. This result validates the effectiveness of our proposed scheme in achieving optimal clustering, UAV deployment, and gateway selection for the system.

Figs. 3 and 4 show the average number of selected gateways and the achievable sum rate of the system versus $\omega$ for different $K$ and both $\alpha = 0$ and $\alpha = 1$. In low $\omega$, the second term of the multi-objective function (20a) is dominant. Since the transmission power of FSO links is significantly lower than that of RF links, the gateway selection algorithm tends to choose more gateways. Fig. 3 demonstrates that for both $\alpha = 0$ and $\alpha = 1$, the number of selected gateways decreases as $\omega$ increases. When $\alpha = 1$ and the UAVs are not acting as gateways, the UAV power consumption is significantly higher compared to the case with $\alpha = 0$, the maximum number of gateways is still chosen. At $\omega = 0.5$, there is a sudden decrease in the selection of gateways as the impact of the first term (20a) becomes more pronounced. It can also be seen that the number of devices does not have much effect on the average number of selected gateways, because it does not directly affect the multi-objective function (20a), and the decision process for gateway selection is the same for different numbers of devices.

Fig. 4 demonstrates that as $K$ increases, the achievable sum rate of the system decreases. This can be explained as follows. On the one hand, the UAV is compelled to utilize paths with low $A_i^{U2G}$ to send the data of the added devices to the gateway. However, these paths do not significantly enhance the achievable sum rate of the system compared to paths with high $A_i^{U2G}$. Weak paths of U2G links generally have lower data rates compared to other hops. On the other hand, more interference occurs, which reduces the D2U hop data rate. Also, the data rate of the G2S hop for each device decreases as the FSO link data rate needs to be divided among more devices. In this case, when the data rate of the G2S hop becomes lower than the data rate of other hops and acts as the limiting link, it leads to a decrease in the overall achievable sum rate of the system. Overall, the second and third fact dominates over the first one, resulting in a decrease in the achievable sum rate.
Fig. 3: Average number of gateway versus $\omega$ for different $K$ and both $\alpha = 0$ and $\alpha = 1$.

Fig. 4: Achievable sum rate of system versus $\omega$ for different $K$ and both $\alpha = 0$ and $\alpha = 1$.

Fig. 5: Comparison of the multi-objective function by adopting different schemes versus $\omega$. (a) $\alpha = 0$. (b) $\alpha = 1$.

of the system with an increase in $K$. Moreover, it has been demonstrated that for $\omega > 0.5$ and fewer gateways, the third fact has a greater influence, leading to a larger decrease in the achievable sum rate of the system compared to $\omega < 0.5$.

To evaluate the advantages of the proposed algorithm, we compare the performance of the multi-objective function of the cross-tier resource allocation problem under different schemes, including proposed Scheme 2, proposed scheme without power optimization, scheme with clustering only, and scheme with random gateway selection. Proposed Scheme 2 is presented as a method that utilizes the alternating iterative optimization approach to solve the second subproblem. This approach involves an iteration loop that begins by optimizing $\mathbf{A}_{U2G}$ using the SA algorithm, considering the maximum transmission power of $\text{UAV}_V$ to $\text{UAV}_G$. Subsequently, the optimization of $\mathbf{P}_U$ is carried out by solving the UAV power optimization problem with CVX. However, in Algorithm 2, Joint UAV power optimization, gateway selection, and U2G channel allocation are carried out simultaneously using the SA algorithm.

Fig. 5 shows the comparison of the objective function of problem (25) versus $\omega$ for both $\alpha = 0$ and $\alpha = 1$. From the comparison of different schemes, it can be observed that our proposed scheme outperforms the others. As can be seen, the joint optimization of UAV power, gateway selection, and U2G channel allocation by the SA algorithm in the proposed scheme leads to an average performance improvement of 48% for $\alpha = 1$ and 67% for $\alpha = 0$, compared to when only clustering is done. The proposed Scheme 2 is introduced as a method with reduced complexity compared to the proposed scheme. However, it is observed that for a specific value of $\omega$, where the proposed scheme achieves the maximum number of selected gateways, the performance of proposed Scheme 2 is equivalent to that of the proposed scheme. However, for other values of $\omega$, proposed Scheme 2 converges to a local optimum.

Figs. 6 and 7 show the total UAV transmission power ($P_{\text{UAV}}^t$) and the total UAV power consumption ($P_{\text{UAV}}$) versus number of UAVs for different $\omega$ and $\alpha = 1$. For Fig. 6, the number of IoRT devices is 20 and the number of UAV antennas is 4. For $U = 5$, UAVs have to use all available paths to communicate with the corresponding gateway to send their data (including the paths with low $\lambda_{U2G}^i$). Fig.
Fig. 6: Total UAV transmission power ($P_{UAV}^t$) versus $U$ for different $\omega$ and $\sigma = 1$.

Fig. 7: Total UAV power consumption ($P_{UAV}$) versus $U$ for different $\omega$ and $\sigma = 1$.

Fig. 8: Achievable sum rate of system versus $U$ for different $\omega$ and $\sigma = 1$.

Fig. 9: Achievable sum rate of system versus $M$ for different $\omega$ and $\sigma = 1$.

6 shows that as the number of UAVs increases, total UAV transmission power decreases until it reaches a constant level. This reduction in power can be attributed to the UAVs getting closer together. Additionally, as the number of UAVs increases, the number of available paths also increases, allowing for the selection of more favorable paths with larger $\lambda_f^{1/U2G}$. This effect intensifies as $\omega$ increases and the number of gateways decreases. Consequently, it can be observed that the green curve ($\omega = 0.9$) has a steeper slope compared to the others, and for $\omega = 0.1$, in which most UAVs act as gateways, total UAV transmission power does not decrease significantly with an increase in the number of UAVs.

In contrast, Fig. 7 illustrates that the total UAV power consumption increases with an increase in $U$, while $P_{UAV}^t$ decreases. This is because as $U$ increases, more UAVs utilize the U2G link, leading to the dominance of the term $P_{UAV}^c$ over $P_{UAV}^t$. However, for $\omega = 0.1$, in which the majority of UAVs act as gateways, $P_{UAV}$ does not increase with an increase in $U$.

Figs. 8 and 9 show the achievable sum rate of the system for different $\omega$ and $\sigma = 1$ versus number of UAVs and number of UAV antennas. In both figures, it can be observed that with a decrease in $\omega$ and consequently increase in gateways that use FSO link, the achievable sum rate of the system increases. The maximum rate is achieved when all UAVs are acts as gateways or have no limiting U2G link data rate.

In Fig. 8, it can be observed that as the number of UAVs increases, there is an improvement in the achievable sum rate of the system. This improvement can be attributed to the increase in the number of devices connected to each UAV and the reduced utilization of weak paths.

In Fig. 9, increasing the number of UAV antennas leads to an enhancement in the achievable sum rate of the system. This improvement arises from the higher data rates achieved on both D2U and U2G links.

VI. CONCLUSION

In this paper, a new model of SAGIN has been investigated to collect data from IoRT devices. SAGIN guarantees coverage of the highly remote areas that can not be covered by terrestrial
wireless access networks. In our proposed SAGIN model, multi-antenna UAVs have been used to improve the antenna gain, multiplexing gain, and diversity gain, by connecting to each other using SVD beamforming. FSO communication has also been used for G2S links to improve the performance of SAGIN. Aiming to minimize the total UAV power consumption considering the limitations of the number of gateways for long-distance communication, we have formulated an optimization problem for gateway selection, channel allocation, UAV deployment, and UAV power allocation. To solve the proposed NP-hard and non-convex problem, a two-step scheme has been devised by jointly adopting constrained k-means clustering, SA method, and SCA method. The effectiveness of our proposed scheme in achieving optimal clustering, UAV deployment, and gateway selection for the system has been shown by the simulation results. Moreover, the number of gateways required for various scenarios has been provided by the simulation results. As an example, when the objective is to minimize UAV power consumption without taking into account the limitation on the number of gateways, the majority of UAVs are chosen as gateways, resulting in the attainment of the highest data rate. It is noteworthy that our proposed scheme has yielded an average performance enhancement of 48% compared to the scenario where only clustering is implemented.

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