Cooperative UAV-Relay based Satellite Aerial Ground Integrated Networks

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***Abstract*—In the post-5G era, escalating user Quality of Service (QoS) strains terrestrial network capacity, especially in urban areas with dynamic traffic distributions. This paper introduces a Cooperative UAV-relay based Deployment (CUD) framework in Satellite Air Ground Integrated Networks (SAGINs). The CUD strategy deploys a UAV-based relay (UAVr) in an amplify-and-forward (AF) mode to enhance user QoS when terrestrial base stations fall short of network capacity. By combining LEO satellite and UAVr signals using cooperative diversity, the CUD framework enhances the signal to noise ratio (SNR) at the user. Comparative evaluations against existing frameworks reveal significant performance improvements, with the CUD framework showcasing a 32.49% total network capacity increase and 25.39% total energy efficiency enhancement improvement, addressing the evolving demands of next-generation networks effectively.**

***Index Terms*—LEO Satellite, UAV relay, SAGINs, Demand–Supply aware balancing, Cooperative diversity**

I. Introduction

The escalating demand for reliable wireless access, driven by technologies like augmented reality, IoT, and autonomous vehicles, is underscored by Cisco's forecast of 13.1 billion mobile users and 29.3 billion Internet-enabled devices by 2023 [1]. Meeting this demand necessitates new network planning strategies for B5G communications to maintain QoS while accommodating dynamic supply needs—bodies like 3GPP advocate integrating terrestrial with non-terrestrial networks to enhance capacity effectively [2].

Recent efforts focus on integrating terrestrial networks with low earth orbit (LEO) satellites to enhance B5G connectivity. LEO satellite networks, characterized by mega-constellations, promise high-speed broadband access. While satellites have traditionally served rural areas well, urban environments present challenges due to masking effects from weather conditions and terrestrial obstacles, significantly attenuating satellite signals [3]. Deploying unmanned aerial vehicles (UAV-BS) has traditionally been used to inject capacity in terrestrial networks [4]. Rather than deploying UAV-BSs, in this paper, we deploy low-altitude UAV-based relays (UAVr) to overcome the challenges associated with integrating LEO satellites and thus enhance the user QoS. Compared to UAV-BS, the proposed strategy of deploying UAVr is observed to be more energy efficient in addition to meeting the user QoS. Compared to terrestrial relays in heterogeneous networks, UAVr offers mobility to the mobile operator in the network. Unlike terrestrial relays, UAVr can also be deployed in rural or disaster scenarios like floods.

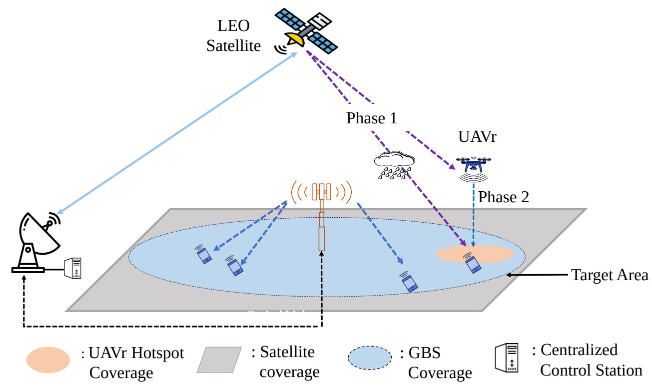

Fig. 1. System model overview.

Our paper introduces a cooperative UAVr deployment (CUD) framework for SAGIN communication networks. Operating within a fixed terrestrial area, our CUD framework strategically places UAVr based on traffic patterns to enhance network capacity and user QoS. By employing cooperative diversity (CD), our framework optimizes signal reception at ground users, utilizing both LEO satellite and UAVr links.

Section II presents the system model, while Section III details the proposed CUD framework. Section IV formulates a network capacity maximization problem and Section IV presents an algorithmic solution framework. Section V shows the simulation results and performance analysis results, while Section VI concludes the paper.

II. System Model

This paper explores downlink resource allocation in a terrestrial network enhanced by UAV relay (UAVr) and LEO satellite assistance, as illustrated in Fig. 1. Ground users are represented by a Poisson point process (PPP) within the Ground Base Station (GBS) coverage area, with their activity monitored across discrete time slots indexed by t, ensuring slot stability. A centralized control station (CCS) oversees the UAVr operation and manages user association and UAVr movements. Mobile user terminals in this network support hybrid communication, connecting with LEO satellites, UAVr, and the GBS [5].

A. Signal model

In this subsection, we introduce the signal model for the LEO-assisted UAVr communication framework. The framework comprises a dual-hop cooperative diversity system involving an LEO satellite, UAVr, and ground users, each equipped with L antennas. We assume the user communicates with the UAVr and LEO satellites in the same sub−6 Ghz frequency band and with the GBS in different bands at the same sub−6 Ghz frequencies.

The channel coefficients linking the satellite to the ground user antenna are denoted by $h_0 = \left(\hbar_{i,s_l}\right)^T$, where l ranges from 1 to L, i denote user, and s denote the LEO satellite. The channel coefficients between satellite and UAVr are expressed as $h_1 = \left(\hbar_{j,s}\right)^T$, where j denote the UAVr. Similarly, the channel coefficients between UAVr and ground user antenna are denoted by $h_2 = \left(\hbar_{i,j_l}\right)^T$, where l varies from 1 to L. It may be noted that superscripts $(.)^T$ and $(.)^\dagger$ denote the transpose and transpose conjugate, respectively. Let's assume that the satellite transmits a signal x_{sym} with an average power of P_s^{tx} to the user during the first phase. The signal received at UAVr from the satellite is given by $r_s^{j,s} = h_1 x_{\text{sym}} + n_1$, and the signal received at the user from the satellite is $r_s^{i,s} = h_0 x_{\text{sym}} + n_0$. While the satellite remains silent during the second phase, UAVr retransmits a scaled version of the received satellite signal in fixed-gain AF mode, with the average transmit power from UAVr to the user, $r_s^{i,j} = h_2 \mathcal{G}(r_s^{j,s}) + n_2 = h_2 \mathcal{G} h_1 x_{\text{sym}} + h_2 \mathcal{G} n_1 + n_2$. The above dual-hop cooperative communication framework at the user end is written as

$$\mathbf{r}_s^{\text{Tot}} = \mathbb{H} x_{\text{sym}} + \mathbb{N} \tag{1}$$

where $\mathbf{r}_s^{\text{Tot}} = \begin{bmatrix} r_s^{i,s} \\ r_s^{i,j} \end{bmatrix}, \mathbb{H} = \begin{bmatrix} h_0 \\ h_2 \mathcal{G} h_1 \end{bmatrix}, \mathbb{N} = \begin{bmatrix} n_0 \\ h_2 \mathcal{G} n_1 + n_2 \end{bmatrix}$, $\text{n}_\iota, \iota = \{0, 1, 2\}$, Denote L dimensional additive white Gaussian's noise (AWGN) vectors and are modeled as identical and independent random variables, i.e., $n_0, n_1, n_2 \sim \mathcal{CN}(0, \sigma^2)$, and $\mathcal{G}$ denotes the fixed-gain factor at the UAVr.

B. Channel Model

This subsection discusses the channel between the LEO satellite and the user, the UAVr, and the UAVr to the user.

1) UAVr to user: The spatial 3D coordinates of a UAVr is denoted as $U_j^{\text{3D}}(t) = (x_j(t), y_j(t), h_j^{\text{Ur}}(t))$. Consequently, the horizontal separation between UAVr and ground user can be expressed as:

$$r_{i,j}(t) = \sqrt{(x_j(t) - x_i)^2 + (y_j(t) - y_i)^2}. \tag{2}$$

Referring to equation (2), we can define the Euclidean distance between UAVr and ground user as

$$d_{i,j}(t) = \sqrt{r_{i,j}^2(t) + (h_j^{\text{Ur}})^2(t)}. \tag{3}$$

The user's path loss is determined using the air-to-ground channel model from [6], considering both line of sight (LoS) and non-line of sight (NLoS) scenarios:

$$PL_{d_{i,j}}^{\text{LoS}}(t) = 20\log_{10}\left(\frac{4\pi f_c d_{i,j}(t)}{c}\right) + \eta_{\text{LoS}}, \tag{4}$$

$$PL_{d_{i,j}}^{\text{NLoS}}(t) = 20\log_{10}\left(\frac{4\pi f_c d_{i,j}(t)}{c}\right) + \eta_{\text{NLoS}}. \tag{5}$$

Here, η_{LoS} and η_{NLoS} represent additional losses due to LoS and NLoS links. The probability of LoS signals from UAVr to the ground user is given by: $P_{d_{i,j}}^{\text{LoS}}(t) = \frac{1}{1+a\exp\left(-b\left(\frac{180}{\pi}\theta_{i,j} - a\right)\right)}$, where $\theta_{i,j} = \tan^{-1}\left(\frac{h_j^{\text{Ur}}(t)}{r_{i,j}(t)}\right)$ and a, b are environmental factors. The probability of NLoS signals is $P_{d_{i,j}}^{\text{NLoS}}(t) = 1 - P_{d_{i,j}}^{\text{LoS}}(t)$. The channel gain $\hbar_{i,j}$ between the UAVr and the user is defined as [7]

$$\begin{aligned}\hbar_{i,j}(t) = &\mathfrak{g}_{i,j}\left(\frac{4\pi f_c d_{i,j}(t)}{c}\right)^{-\frac{\alpha_{exp}^{(3)}}{2}} \\ &\times 10^{-\frac{P_{d_{i,j}}^{\text{LoS}}(t)\times PL_{d_{i,j}}^{\text{LoS}}(t) + P_{d_{i,j}}^{\text{NLoS}}(t)\times PL_{d_{i,j}}^{\text{NLoS}}(t)}{20}},\end{aligned} \tag{6}$$

Here, $d_{i,j}$ represents the distance between a UAVr and a user, $\alpha_{exp}^{(3)}$ denotes the path loss exponent from the UAVr to the user, and $\mathfrak{g}_{i,j}$ signifies the small-scale fading component of the link channel between the UAVr and the user. The average path loss of the signal from UAVr to the ground user is

$$\begin{aligned}PL_{d_{i,j}}^{\text{Avg}}(t) &= P_{d_{i,j}}^{\text{LoS}}(t) \times PL_{d_{i,j}}^{\text{LoS}}(t) + P_{d_{i,j}}^{\text{NLoS}}(t) \times PL_{d_{i,j}}^{\text{NLoS}}(t) \\ &= \frac{A}{1 + a\exp\left(-b\left[\frac{180}{\pi}\theta_{i,j} - a\right]\right)} + 20\log_{10}\left(d_{i,j}(t)\right) + \beta,\end{aligned} \tag{7}$$

where $\beta = 20\log_{10}\left(\frac{4\pi f_c}{c}\right) + \eta_{\text{NLoS}}$ and $A = \eta_{\text{LoS}} - \eta_{\text{NLoS}}$.

Let $p_{i,j}$ denote the minimum required transmission power to send a signal from the UAVr to the ground user. For the signal transmission to succeed, the received signal-to-noise ratio (SNR) $\gamma_{i,j}(t)$ at a user. Hence, the SNR for users associated with UAVr can be expressed as

$$\gamma_{i,j}(t) = \frac{p_{i,j}.\left\|\hbar_{i,j}(t)\right\|^2}{B_{i,j}\sigma^2}, \tag{8}$$

The hovering power of the UAVr is computed as

$$p_j^{\text{Hov}} = p_0(1 + \Delta)e^{\varepsilon h_j^{\text{Ur}}/2}. \tag{9}$$

Here, p_0 denotes the power the active UAVr utilizes during hovering. Δ and ϵ are constants, while h_j^{Ur} indicates the altitude of the UAVr [8]. The hovering altitude of the UAVr, corresponding to its hovering power (9), is

$$h_j^{\text{Ur}} = \frac{2}{\epsilon}\ln\frac{p_j^{\text{Hov}}}{p_0(1 + \Delta)}. \tag{10}$$

The total power (communication and hovering) consumption of UAVr is

$$p_j^{\text{Total}}(t) = p_{i,j}(t) + p_j^{\text{Hov}}(t). \tag{11}$$

2) LEO satellite to UAVr and user : In assessing system performance, it is imperative to consider the mobility of LEO satellites, which are non-geostationary. The linkage between a UAVr and a LEO satellite is encapsulated through a visibility parameter $V_{j,s}(t)$, evaluated at discrete time slot t as outlined in [9].

$$V_{j,s}(t) = \begin{cases} 1 & \text{if } \cos\left(\frac{2\pi t}{T_s} - \theta_p\right) \geq \frac{R_E^2 + r_{EC}^2 - d_{SR}^2}{2R_E r_{EC}} \\ 0 & \text{otherwise.} \end{cases} \quad (12)$$

That is, if the LEO satellite is visible at time t, then $V_{j,s}(t) = 1$, else $V_{j,s}(t) = 0$. Sophisticated handover (HO) schemes, like guaranteed and prioritized HO, ensure seamless transitions between LEO satellites and UAVr, maintaining data transmission reliability. The channel gains from satellite to UAVr are described by the shadowed-Rician fading (SRF) model: $\hbar_{j,s} = \sqrt{\mathfrak{g}^{\text{avg}} d_{j,s}^{-\alpha_{exp}^2}}$, where $\mathfrak{g}^{\text{avg}}$ represents average channel gain, $d_{j,s}$ is the satellite-UAVr distance, and α_{exp}^2 denotes the path loss exponent. The SRF component $\mathfrak{g}^{\text{avg}} \sim \text{SR}\ (\wp, \Im, \varnothing)$ includes direct signal average power $\wp$, half average power of the scatter portion $\Im$, and Nakagami-m fading component $\varnothing$.

Additionally, we assume the distances between LEO satellites are similar to those between UAVr and users. The instantaneous SNR for each communication link is determined based on the LEO satellite visibility criterion (12).

$$\gamma_{j,s}(t) = V_{j,s}(t) P_s^{\text{tx}} \left\|\hbar_{j,s}\right\|^2 / \sigma^2 \ . \quad (13)$$

Similarly, the channel gain from satellite to user is expressed as $\hbar_{i,s} = \sqrt{\mathfrak{g}^{\text{avg}} d_{i,s}^{-\alpha_{exp}^2}}$ with the SNR being

$$\gamma_{i,s}(t) = V_{i,s}(t) P_s^{\text{tx}} \left\|\hbar_{i,s}\right\|^2 / (\sigma^2). \quad (14)$$

In this context, P_s^{tx} denotes the average transmission power from the satellite to both the UAVr and user.

3) GBS to user : The user establishes communication with the GBS within the Sub-6 GHz frequency bands. It is presupposed that the user undergoes independent Rayleigh fading while connected to the GBS. At each time slot t, the channel coefficient is

$$\hbar_{i,G}(t) = \mathfrak{g}_{i,G} \left(r_{i,G}(t)\right)^{-\alpha_{exp}}. \quad (15)$$

Here, $\mathfrak{g}_{i,G}$ denotes the small-scale Rayleigh fading gain, following a complex Gaussian distribution, i.e., $g_{i,G} \sim N(0,1)$. $r_{i,G}$ represents the distance between the user and the GBS. Hence, the SNR for users associated with GBS can be defined as

$$\gamma_{i,G}(t) = \frac{P_G^{\text{tr}} \left\|\hbar_{i,G}(t)\right\|^2}{B_{i,G}\sigma^2}, \quad (16)$$

Here, $B_{i,G}$ is the bandwidth allocated to the user and the GBS transmits at a fixed power P_G^{tr} for terrestrial communications. UAVr/Satellite links are utilized only when the GBS cannot serve more users to maximize network capacity. Hence, we introduce a binary indicator $\delta_{i,G}(t)$ for a user who meets the SNR and load conditions under GBS coverage at time t:

$$\delta_{i,G} = \begin{cases} 1, & \text{if } \left(\gamma_{i,G} \geq \gamma_{\text{th}}\right) \wedge \left(|\Omega_G| \leq \omega_G^{\max}\right) \\ 0, & \text{otherwise.} \end{cases} \quad (17)$$

Here, γ_{th} is defined as the predefined SNR threshold for successful signal transmission, Ω_G and $\omega_G^{\max}$ show the current user associated with GBS and the maximum user association capacity of GBS. Therefore, the achievable data rate for users connected to a GBS is

$$c_{i,G}(t) = B_{i,G} \log_2(1 + \gamma_{i,G}(t)). \quad (18)$$

III. UAV Relay Placement and Signal Combining

When the ground base station falls short of meeting user QoS, our CUD method deploys UAVr to the hotspots, leveraging LEO satellites to serve users. In this section, we delve into optimal UAVr placement and signal combining.

A. UAVr coverage analysis

A user falls within coverage if its distance from the center of the coverage region, $r_{i,j}(t)$, satisfies the condition:

$$\delta_{i,j} r_{i,j}^2(t) \leq R_j^2(t). \quad (19)$$

We adapt this equation (19) following [10], resulting in:

$$r_{i,j}^2(t) \leq R_j^2(t) + M(1 - \delta_{i,j}). \quad (20)$$

M is a large constant, indicating significant distance when $\delta_{i,j} = 0$. The user is associated with $\delta_{i,j} = 1$, where $\delta_{i,j} \in \{0,1\}$ serves as an indicator function denoting user association with an access point represented as:

$$\delta_{i,j} = \begin{cases} 1, & \text{if } r_{i,j}^2(t) \leq R_j^2(t) \\ 0, & \text{otherwise.} \end{cases} \quad (21)$$

The following subsection discusses cooperative diversity based signal combining employed within the proposed CUD framework.

B. Cooperative diversity at user

Cooperative communication via LEO satellite-UAVr occurs over two phases: Phase I and Phase II. In Phase I, the LEO satellite sends a signal to both UAVr and ground user simultaneously. UAVr then employs AF protocol in Phase II to relay the signal to the user while the satellite remains silent. Assuming perfect synchronization between signals from the satellite and UAVr at the user, operating in time division duplex mode, our framework prioritizes efficient signal relaying using AF for its simplicity and lower complexity [11].

Then, using the CD at receiver with the weighting vector $\mathbf{w}^\dagger$ can write from (1) the combined output as

$$\mathbf{w}^\dagger \mathbf{r}_s^{\text{Tot}} = \mathbf{w}^\dagger \mathbb{H} \mathbf{x}_{\text{sym}} + \mathbf{w}^\dagger \mathbb{N}. \quad (22)$$

In the presence of complete channel state information (CSI) at the destination, the instantaneous SNR at the user is

$$\gamma_{\text{AF}}(\mathbf{w}) = P_s^{\text{tx}} \frac{\mathbf{w}^\dagger \mathbb{H}\mathbb{H}^\dagger \mathbf{w}}{\mathbf{w}^\dagger \mathscr{R}_n \mathbf{w}} \quad (23)$$

where, $\mathscr{R}_\mathrm{n} = \mathbb{E}\{\mathbb{N}\mathbb{N}^\dagger\}$, and $P_s^{\mathrm{tx}} = \mathbb{E}\left\{\mathbf{x}_{\mathrm{sym}}\mathbf{x}_{\mathrm{sym}}^\dagger\right\}$. Taking the derivative of (23) to the weight vector $\mathbf{w}$ [12], we get the optimal weight vector in a dual-hop cooperative communication system is $\mathbf{w}_{\mathrm{opt}} = c_r \mathscr{R}_n^{-1}\mathbb{H}$. where c_r denotes an arbitrary constant for any $c_r \neq 0$. Using the optimal weight vector, we can obtain the maximum signal [13] in a dual-hop AF cooperative communication is

$$\gamma_{\mathrm{AF,\,max}}^{\mathrm{CD}}(\mathbf{w}_{\mathrm{opt}}) = \gamma_{i,s} + \frac{\gamma_{j,s}\gamma_{i,j}}{\gamma_{i,j} + \varsigma} \tag{24}$$

where $\varsigma = \frac{1}{\sigma^2 \mathcal{G}^2}$.

To represent whether the ground user is associated with the UAVr or not, the indicator function $\delta_{i,j}$ is modified as follows to incorporate the user QoS as well as coverage constraints.

$$\delta_{i,j} = \begin{cases} 1, & \text{if, } \left(\gamma_{\mathrm{AF,\,max}}^{\mathrm{CD}}(t) \geq \gamma_{\mathrm{th}}\right) \wedge (r_{i,j}^2(t) \leq R_j^2(t)) \\ 0, & \text{otherwise.} \end{cases} \tag{25}$$

It is assumed that each user can only connect to UAVr at a time, and such a constraint is written as

$$\sum_{i=1}^{N_\mathrm{U}} \delta_{i,j} = 1, \tag{26}$$

In a time-division cooperative communication scheme, the transmission process is split into two slots: one for the LEO satellite and one for the UAVr. This halves the effective bandwidth for each phase, so the capacity per slot is divided by two to match the overall throughput of a non-cooperative system [14]. Thus, the achievable data rate of the user associated with UAVr and LEO Satellite is obtained from the Shannon theorem, expressed as

$$c_{\mathrm{AF}}^{\mathrm{CD}}(t) = \frac{B_{i,j}}{2}\log_2\left(1 + \gamma_{\mathrm{AF,\,max}}^{\mathrm{CD}}(t)\right). \tag{27}$$

Here, $B_{i,j}$ is the allocated bandwidth (MHz) of the downlink connection from the UAVr to the user and the LEO satellite to the user. According to (27), the data transmission rate achievable by users associated with LEO satellites through UAVr is

$$C_j(t) = \sum_{i \in \ \Omega_j, \forall i \in \{1,2,\ldots,N_\mathrm{U}\}} c_{\mathrm{AF}}^{\mathrm{CD}}(t).\delta_{i,j}(t), \tag{28}$$

Where Ω_j is the set of users associated with UAVr and N_U is the number of users UAVr/LEO Satellite serves collaboratively. The total GBS capacity is computed from the (18) as

$$C_G(t) = \sum_{i \in \ \Omega_G, \forall i \in \{1,2,\ldots,N_\mathrm{G}\}} c_{i,G}(t).\delta_{i,G}(t), \tag{29}$$

Ω_G is the set of users associated with the GBS, and N_G is the number of users served by the GBS cell.

From (11), (28) and (29) we can derived the total energy efficiency as

$$E^{\mathrm{Tot}}(t) = \frac{C_j(t) + C_G(t)}{(p_j^{\mathrm{Total}}(t) + P_G^{\mathrm{tr}}(t))} \tag{30}$$

IV. Problem Formulation and Proposed Solution

We aim to increase the network's total capacity through the proposed CUD approach involving the first placement of UAVr at the desired location, followed by signal combining from the LEO satellite and UAVr.

A. *Problem formulation*

The minimum data rate and user association specifications constrain the problem formulated below. The problem formulation from (28), and (29) along with the constraints, is defined as:

$$\max_{\delta_{i,j}(t),\delta_{i,G}(t),p_{i,j}(t)} (C_j(t) + C_G(t)) \tag{31}$$

The constraints of Eq. (31) are given by

$$\begin{aligned} &\text{subject to (24), (25), (26), (27),} \\ &0 \leq p_{i,j} \leq p_{\max}, && \text{(31a)} \\ &0 \leq |\Omega_j| \leq \omega_j^{\max}, && \text{(31b)} \\ &0 \leq |\Omega_G| \leq \omega_G^{\max}, && \text{(31c)} \\ &r_{i,j}^2(t) \leq R_j^2(t), && \\ &\delta_{i,j} \in \{0,1\},\ \forall i \in \Omega_j, && \text{(31d)} \\ &\delta_{i,G} = 1 - \delta_{i,j},\ \forall i, && \text{(31e)} \end{aligned}$$

Constraints (31a) and (31b) limit transmission power and user associations for each UAVr. Equation (31a) considers UAVr altitude and service duration, while (31b) restricts user associations. Equation (31c) governs user associations with the GBS. Candidate configurations, including UAVr locations U_j^{2D} and coverage radius R_j, derive from relationships in (31d), obtained from (25) and Constraint (31e) ensures each user is associated with either the GBS or the UAVr-satellite, not both. For user, $\delta_{i,G} = 1$ indicates GBS association, while $\delta_{i,j} = 1$ indicates UAVr-satellite association.

Problem (31) presents a non-convex mixed-integer programming challenge due to the complex mathematical formulation of successful transmission and the integer association constraint (25). Solving such problems typically falls outside the realm of polynomial computational complexity [15]. However, optimizing transmission power with a fixed user association becomes significantly more manageable [16]. Therefore, we introduce a CUD-based approach to optimize the UAVr transmission power $p_{i,j}$ by fixing the association variable $\delta_{i,j}$.

B. *Proposed solution*

Algorithm 1 presents the pseudo-code for the main procedure of the proposed CUD. The CCS executes this procedure. Key steps within the CUD procedure are outlined below:

- The initial phase (Step 1) involves preparing temporary matrices by the CCS, storing information for subsequent re-association and optimization.
- Step 4 systematically examines for overload conditions using a for-loop.
- Step 5 monitors excess users through a while loop. The CCS initiates re-association and transmission power optimization until all excess users are re-associated.

Algorithm 1 Cooperative signal combining based UAVr deployment framework

Input: $\omega_j^{\max}, \omega_G^{\max}, \Omega, \Omega_G^{\text{Ex}}, D_j^{\text{th}}$

1: Consider two types of hotspots:
2: a) Density-based: $\omega_j^{\max} = D_j^{\text{th}} * \pi * R_j^2$
3: b) User-based: Ω_G^{Ex}=$(\Omega_G - \omega_G^{\max})$
4: **for** $j = 1$ **do**
5: **while** $(\omega_G^{\max} > 0 \vee \Omega_j^{\text{Ex}} > 0) \wedge V_{j,s} = 1 \wedge \gamma_{i,s} < \gamma_{\text{th}}$ **do**
6: Select hotspot user i^* from Ω_G; then send UAVr U_j^* to serve i^*;
7: **for** $j = 1$ **do**
8: **for** $i = i$ to $|\mathbf{\Omega_j}|$ **do**
9: Update distance: $\mathbf{d}\left(i^*, j^*\right) = \sqrt{\mathbf{r}^2\left(i^*, j^*\right) + h_j^2}$
10: Determine average path loss and minimum power for SNR: $PL^{\text{Avg}}_{h_j^{\text{Ur}}, r_{i^*, j^*}}$, $p^{\min}_{i^*, j^*}$
11: Find optimal power p_{i^*, j^*} [8] to maximize Eq.31
12: **if** $p^{\min}_{i^*, j^*} \leq p_{\max}$ **then**
13: **if** $p_{i^*, j^*} \leq p^{\min}_{i^*, j^*}$ **then**
14: $p_{i^*, j^*} = p^{\min}_{i^*, j^*}$
15: **else if** $p_{i^*, j^*} \geq p_{\max}$ **then**
16: $p_{i^*, j^*} = p_{\max}$
17: **end if**
18: **else**
19: $p_{i^*, j^*} = p_{\max}$
20: **end if**
21: Transmit power: $\mathbf{P}\left(i^*, j^*\right) = p_{i^*, j^*}$
22: **end for**
23: **end for**
24: **end while**
25: **end for**
26: Send $\mathbf{\Omega}$ and $\mathbf{P}$ to all UAVr

TABLE I
SIMULATION PARAMETERS

Parameter	Symbol	Value
Environmental parameters	$a, b, \eta_{\text{LoS}}, \eta_{\text{NLoS}}$	9.61, 0.16, 1, 20
Maximum path loss	$PL^{\max}_{d_{i,j}}$	119 dB
LEO Satellite Altitude	h_s	1000 km
UAVr Altitude and Radius	h_j^{Ur}, R_j	30m, 100m
UAVr and GBS Number	U_j, G	1, 1
Allocated Bandwidth	$B_{i,j}$	20 MHz
Noise Power	σ^2	-174 dBm/Hz
Total Number of Users	i	200
Max Associations at UAVr	$\omega_j^{\max}$	100
Max Associations at GBS	$\omega_G^{\max}$	100
SNR Threshold	γ_{th}	3 dB
Max Transmission Power	$p_{\max}$	29 dBm

- Step 6 selects i^* from Ω_{G}, determining the sector of the user-generated hotspot.
- A new for loop (Steps 7 to 25) optimizes transmit power for each UAVr with CCS assistance.
- Step 9 computes the Euclidean distance between the UAVr and i-th user.
- Step 10 updates the path loss of the association link and determines the minimum required transmit power.
- Step 11 finds the optimal transmit power to maximize (31).
- Steps 12 to 20 check transmit power constraints and commit updated values.
- Finally, the CCS sends updated parameter sets, $\mathbf{\Omega}$ and $\mathbf{P}$, to all UAVr for deployment updates.

V. Results and Discussion

This section evaluates the problem (31) based on key performance metrics: total capacity and energy efficiency. Fixed adaptive UAVr deployment within a defined area and varying user generation (temporary hotspot) form the basis of our simulations, validating the effectiveness of the proposed CUD approach. Furthermore, comparisons are drawn with Equal Gain Combining-based SAGIN (EGC-SAGIN), Selection Combining-based SAGIN (SC-SAGIN), LEO satellite ground base station (LEO-GBS), and ground base station only (GBS-Only) frameworks.

A. Simulation setting

Simulations were conducted in MATLAB R2020b, focusing on an urban setting, with parameter values detailed in Table I. Subsequent subsections delve into the pivotal results and insights regarding network capacity and energy efficiency.

B. Simulation results

In Fig. 2, we compare the performance of CUD with state-of-the-art frameworks across varying UAVr counts. CUD consistently outperforms other setups in total network capacity, achieving gains of up to 32.49% compared to the GBS-only framework. Regarding EGC-SAGIN, SC-SAGIN, and LEO-GBS frameworks, CUD achieves enhancements of up to 3.65%, 6.92%, and 29.59%, respectively. The capacity improvements by CUD, facilitated by strategic UAVr deployment and CD-based signal combining, underscore its efficacy over existing non-SAGIN configurations. These findings highlight the rationale for operators to consider SAGIN-based network architectures.

Fig. 2. Illustrating the variation of network capacity with the number of users. Scaling factors have been applied to certain data series for improved visibility: AMUD (Scaled by 1.16), EGC-SAGIN (Scaled by 1.12), SC-SAGIN (Scaled by 1.08), LEO-GBS (Scaled by 1.04), and GBS-Only (Scaled by 1.00).

In Fig. 3, we compare the performance of the proposed CUD with existing frameworks across varying UAVr numbers. The CUD consistently outperforms other setups in total network energy efficiency, achieving gains of up to 25.39% over conventional GBS-only systems. Compared to EGC-SAGIN, SC-SAGIN, and LEO-GBS frameworks, the CUD exhibits improvements of up to 3.65%, 6.93%, and 28.54%, respectively. These results highlight the significant enhancements in energy efficiency enabled by the CUD strategic UAVr deployment and CD-based signal combining.

Remark 1. *The proposed AMUD framework achieves up to 32.49% higher capacity than state-of-the-art methods, primarily due to adaptive UAVr placement and the CUD scheme. These significant capacity gains over non-SAGIN frameworks highlight the advantages of integrating SAGIN-based architectures. Moreover, the CUD approach accommodates varying user densities, ensuring energy-efficient communication under fluctuating network loads. This underscores the potential of UAVr and satellite technologies in future communication networks, particularly in scenarios with dynamic user demands.*

The observed performance decline of the LEO-GBS framework for total energy efficiency compared to GBS-Only with increasing user numbers can be attributed to resource allocation constraints and significant path loss due to the distance between LEO satellites and ground users.

Fig. 3. Illustrating variation of network energy efficiency with number of users. Scaling factors have been applied to certain data series for improved visibility: AMUD (Scaled by 1.16), EGC-SAGIN (Scaled by 1.12), SC-SAGIN (Scaled by 1.08), LEO-GBS (Scaled by 1.04), and GBS-Only (Scaled by 1.00).

VI. Conclusion

The paper introduces a Cooperative signal combining-based UAVr deployment strategy in SAGINs. This approach leverages the adaptive deployment of a UAVr in an AF system to enhance the SNR at the user. The CUD framework strategically deploys UAVr in response to fluctuating user traffic, optimizing user SNR through the cooperative diversity technique. By fostering intelligent and cooperative communication between LEO-user and UAVr-user links, the proposed CUD framework demonstrates significant enhancements in network capacity and energy efficiency at higher UAVr densities. The study highlights the potential of integrating aerial UAVr and LEO satellite-based technologies in future urban communication networks.

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