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Cooperative UAV-Relay based Satellite Aerial Ground Integrated Networks

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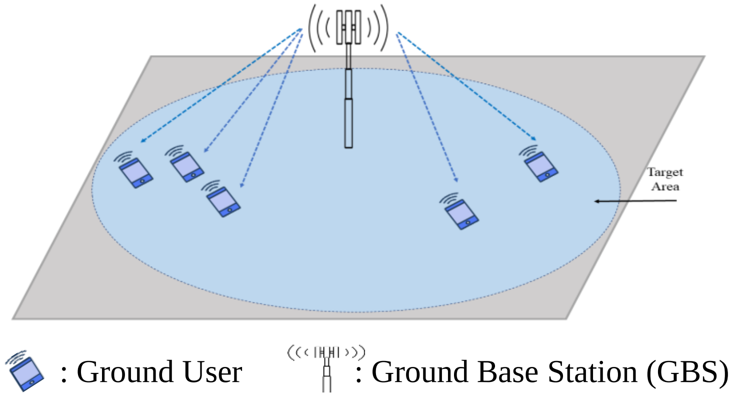
Introduction

- Terrestrial Base Stations (GBS) design to serve fixed number of users, ensuring Quality of Service (QoS)
    - QoS declines when user demand exceeds capacity.
- By 2023, mobile devices expected to reach 13.1 billion and IoT devices 29.3 billion (Cisco), driving the demand[1]
    - User mobility creates temporary hotspots, causing service disruptions more frequently



GBS Coverage

Current Solutions:

- *Deploy Ground Relays*: Expands coverage but can be costly.
- *Temporary UAV Base Stations (UAV-BS):* Offers flexible support for varying demands.
- *LEO Satellite-Assisted Communication*: Enhances connectivity and reduces disruptions.

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[1] Y. Liu *et al.*, "Evolution of NOMA toward next-generation multiple access (ngma) for 6G," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 4, pp. 1037– 1071, 2022.

Motivation and Objective

Current Limitations

- *Fixed User Association*: GBS struggle to adapt to dynamic user densities and mobility.
- *High Costs*: Additional GBS relays for temporary use are expensive and inefficient.

Research Gaps

- *Lack of Studies*: Limited exploration of adaptive UAV relays with GBS and LEO satellite backhaul.

Improvement Strategies (Objective)

- *UAV-Relay (UAVr):* Enhances energy efficiency compared to UAV-BS.
- *Dynamic Deployment*: Positioning UAVr based on temporary hotspots for optimized service.
- *Cooperative Communication*: Collaboration with LEO satellites improves signal-to-noise ratio (SNR).
- *Quality Assurance*: Focus on maintaining high communication quality while maximizing capacity.

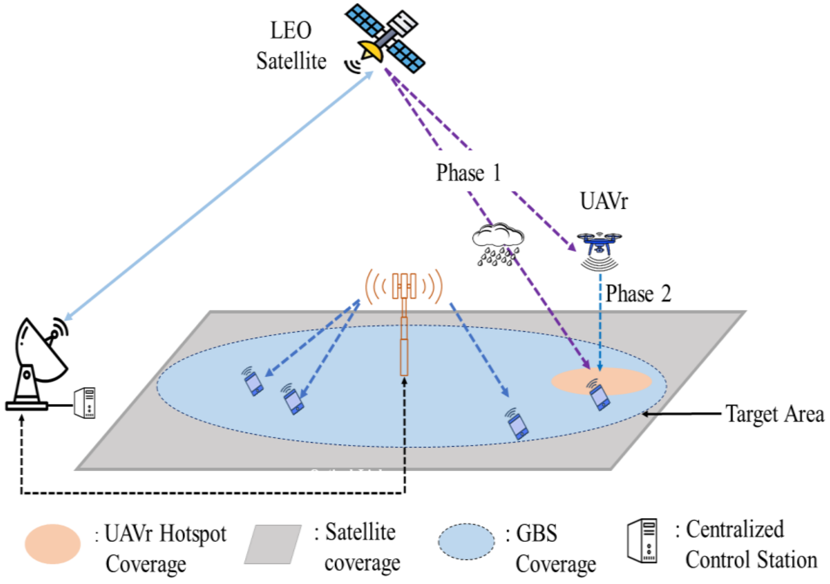
System Model and Key Contribution

System Model:

- *User Distribution*: Poisson point process (PPP)
- *Central Control Station (CCS)*: manages UAVr and user associations
- *Hybrid Communication*: Users can connect to LEO, UAVr, and GBS[1]

Key Contributions:

- *CUD* Framework*: First to integrate UAVr and LEO for cooperative diversity
- *Signal Quality*: Improved SNR by combining UAVr and LEO signals
- *Capacity Improvement*: Optimizes user association and power for higher total capacity



System Model Overview.

*CUD: cooperative UAV-relay deployment

[1] X. Fang *et al.*, “5G embraces satellites for 6G ubiquitous iot: Basic models for integrated satellite terrestrial networks,” *IEEE IoT J.*, vol. 8, no. 18, pp. 14 399–14 417, 2021.

Signal Model: dual-hop cooperative system

- LEO satellite-UAVr signal:

$$\boldsymbol{r_s^{i,s} = h_0\, x_{sym} + n_0}$$

- LEO satellite-user signal,

$$\boldsymbol{r_s^{j,s} = h_1 x_{sym} + n_1}$$

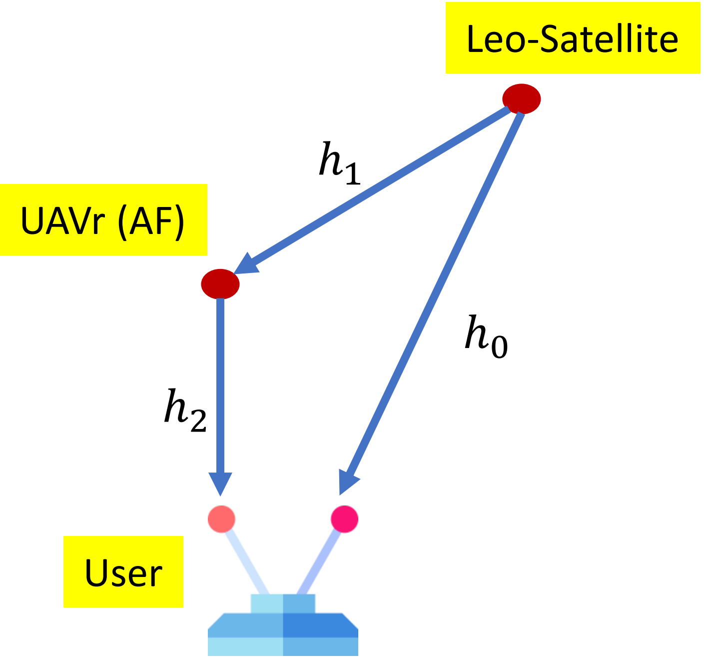
- UAVr-user signal,

$$\boldsymbol{r_s^{i,j} = h_2 g\left(r_s^{j,s}\right) + n_2 = h_2 g h_1 x_{sym} + h_2 g n_1 + n_2}$$

- During the two hops, overall signals at user:

$$r_s^{\text{Tot}} = \mathbb{H} x_{\text{sym}} + \mathbb{N}$$

where, $r_s^{\text{Tot}} = \begin{bmatrix} r_s^{i,s} \\ r_s^{i,j} \end{bmatrix}$, $\mathbb{H} = \begin{bmatrix} h_0 \\ h_2 g h_1 \end{bmatrix}$, $\mathbb{N} = \begin{bmatrix} n_0 \\ h_2 g n_1 + n_2 \end{bmatrix}$, x_{sym}= satellite transmits power, g=fixed gain factor, n_0, n_1, n_2 is Noise, $\mathbf{h_0} = (\hbar_{i,s})^{\mathrm{T}}$, $\mathbf{h_1} = (\hbar_{j,s})^{\mathrm{T}}$, and $\mathbf{h_2} = (\hbar_{i,j})^{\mathrm{T}}$ channel coefficients LEO-User, LEO-UAVr, and UAVr-User.



- **No. of Antenna use:**
- LEO Satellite and UAVr used single antenna
- At user: two (direct+ Cooperative)

Channel Model: LEO Satellite to UAVr and User

- SNR for UAVr associated with LEO satellite

$$\gamma_{j,s}(t) = \frac{V_{j,s}(t) p_s^{\text{tx}} \left\| \hbar_{j,s}(t) \right\|^2}{B_{j,s}\sigma^2}$$

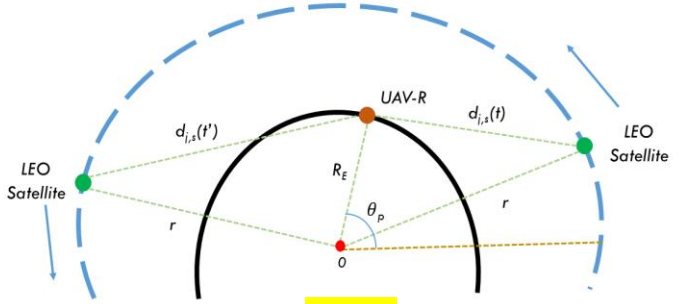
- SNR for User associated with LEO Satellite

$$\gamma_{i,s}(t) = \frac{V_{i,s}(t) p_s^{\text{tx}} \left\| \hbar_{i,s}(t) \right\|^2}{B_{i,s}\sigma^2}$$

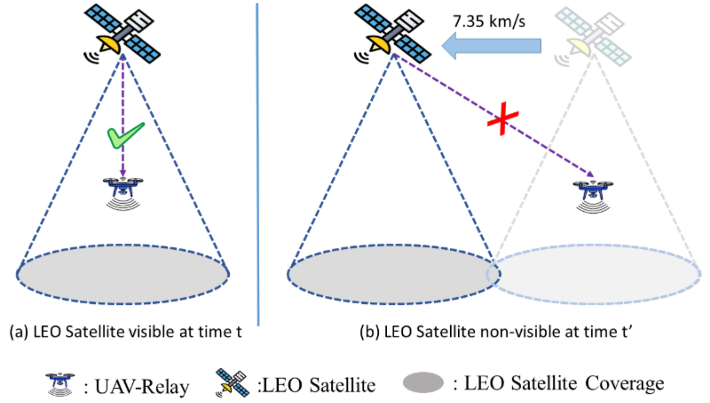
- The link visibility parameter[1]

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

R_E= Earths radius, θ_p=polar angle, r_{EC}= satellite and earth distance, d_{SR}=slant range, T_s=Orbital period to complete a full orbit around earth



(a)



(a) LEO Satellite visible at time t

(b) LEO Satellite non-visible at time t'

(b)

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[1] W. Abderrahim, O. Amin, M.-S. Alouini, and B. Shihada, "Proactive traffic offloading in dynamic integrated multi-satellite terrestrial networks," *IEEE Trans. Commun.*, vol. 70, no. 7, pp. 4671–4686, 2022.

Channel Model: GBS to User

- SNR for user associated with GBS

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

- The allocated data rate associated with GBS

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

- User data rate associated with GBS:

$$C_G(t) = \sum_{i\,\epsilon\,\Omega_G,\forall i\in\{1,2,\ldots,N_G\}} c_{i,G}(t)$$

- where User association indicator $\delta_{i,G}$ for GBS

$$\delta_{i,G}(t) = \begin{cases} 1, & \text{if, } \overbrace{(\gamma_{i,G} \geq \gamma_{\text{th}})}^{\text{Signal constraints}} \wedge \overbrace{(|\Omega_G| \leq \omega_G^{\max})}^{\text{Load constraints}} \\ 0, & \text{otherwise} \end{cases}$$

- ➢ $\gamma_{i,G}$ = SNR from GBS
- ➢ γ_{th} = threshold SNR
- ➢ Ω_G= set of user associated with GBS
- ➢ $\omega_G^{\max}$= user association capacity of GBS
- ➢ i = 1,…, N_G = user associated with GBS
- ➢ $c_{i,G}$ = Allocated data rate

Channel Model: Cooperative Communication

- SNR for User associated with UAVr

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

- The instantaneous signal after amplify and forward (AF) defined

$$\gamma_{\text{AF,max}}^{\text{WCD}} = \gamma_{i,s} + \frac{\gamma_{j,s}\gamma_{i,j}}{\gamma_{i,j} + \varsigma}$$

- User allocated data rate associated with UAVr:

$$C_{\text{AF,max}}^{\text{WCD}}(t) = B_{i,j}\log_2\left(1 + \gamma_{\text{AF,max}}^{\text{WCD}}(t)\right)\,\delta_{i,j}(t)$$

- User data rate associated with UAVr/Satellite:

$$C_j(t) = \sum\nolimits_{i\,\epsilon\,\Omega_j,\forall i\in\{1,2,\dots,N_U\}} C_{\text{AF,max}}^{\text{WCD}}(t)$$

where user association indicator $\delta_{i,j}$ for UAVr

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

- $\gamma_{\text{AF,max}}^{\text{WCD}} = \text{max SNR at user}$
- $r_{i,j}$= horizontal distance between UAVr and user
- R_j= max UAVr radius, and $C_j(t)$ =User data rate associated to UAVr
- j= number of UAVr, and i= 1,…, N_U = user associated with UAVr
- $\Omega_j = \max(0, |\Omega_{\text{Tot}}| - \omega_G^{\max})$ =user set associated to UAVr/Satellite
- Ω_{Tot}=total set of users

Energy Efficiency and Power

- **Total power**: Communication ($p_{i,j}$) and UAVr Hover (p_j^{Hov})[1]

$$p_j^{\text{Tot}}(t) = p_{i,j}(\text{t}) + p_j^{\text{Hov}}(t)$$

- Total Capacity, C^{Tot}

$$C^{\text{Tot}}(t) = \left(C_j(t) + C_G(t)\right)$$

- Total Energy Efficiency, E^{Tot}

$$E^{\text{Tot}}(t) = \frac{C^{\text{Tot}}(t)}{\left(P_j^{\text{Tot}} + P_G^{\text{tr}}\right)}$$

UAVr Coverage

- A user falls within the UAVr coverage if its distance from the center of the UAVr coverage region, $r_{i,j}$, satisfies the condition[2]

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

where R_j denotes the UAVr coverage radius, M denote large constant and $\delta_{i,j}$ is

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

- R_j= max UAVr radius, and
- $C_j(t)$ =User data rate associated to UAVr
- j= number of UAVr
- i= 1,..., N_U = user associated with UAVr

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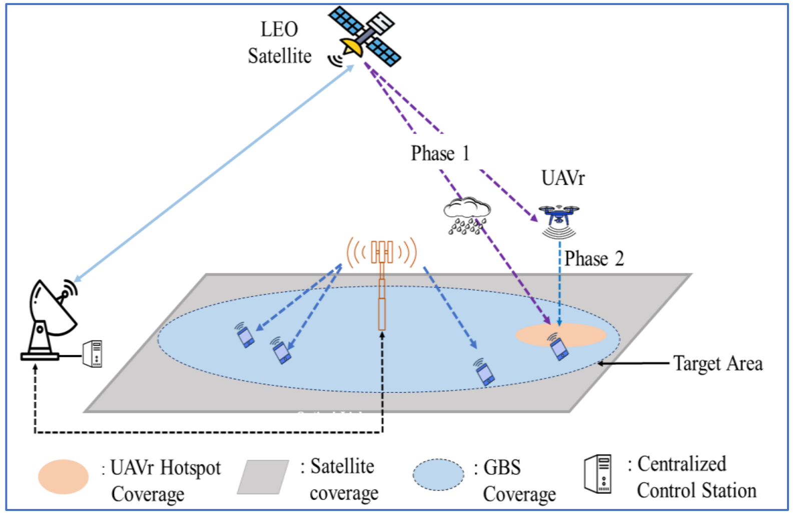
[1] C.-C. Lai *et al.*, "Adaptive and fair deployment approach to balance offload traffic in multi-UAV cellular networks," *IEEE Trans. Veh. Technol.*, vol. 72, no. 3, pp. 3724–3738, 2023.

[2] M. Alzenad *et al.*, "3-D placement of an unmanned aerial vehicle base station (UAV-BS) for energy-efficient maximal coverage," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 434–437, 2017.

1. Maximize the capacity UAVr associated users C_j
2. Maximize the capacity of GBS associated users C_G



Problem Formulation

$$\max_{\delta_{i,j},p_{i,j}} C^{\text{Tot}} = \max_{\delta_{i,j},p_{i,j}} \left(\underbrace{C_j(t)}_{\textcircled{1}} + \underbrace{C_G(t)}_{\textcircled{2}}\right)$$

s.t.

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

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

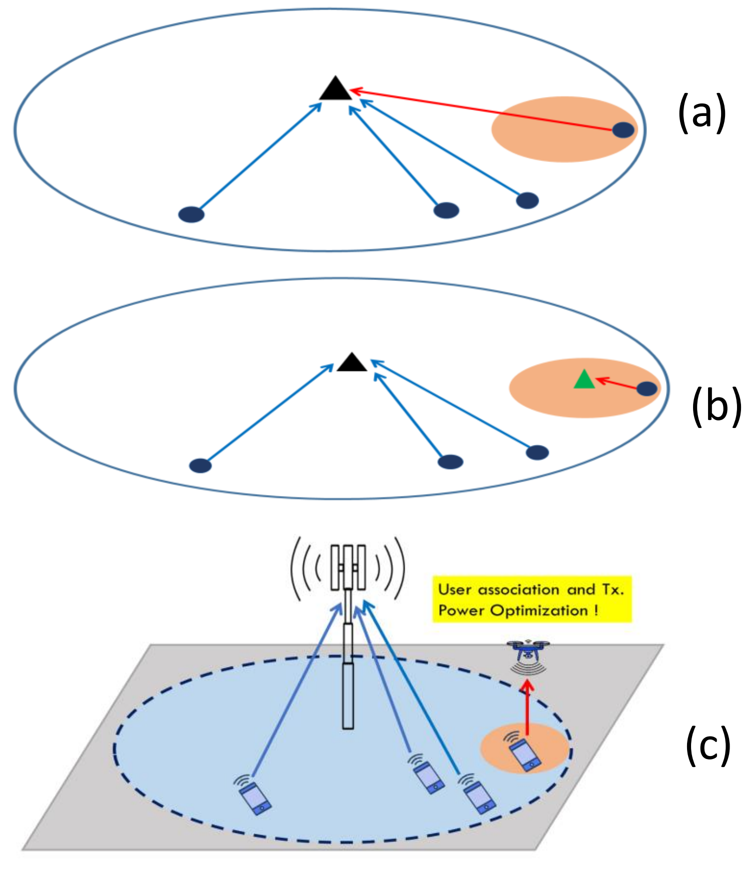
Constraints

$$0 \leq p_{i,j} \leq p_{\max}$$
$$0 \leq |\Omega_j| \leq \omega_j^{\max}$$
$$0 \leq |\Omega_G| \leq \omega_G^{\max}$$
$$r_{i,j}^2 \leq R_j^2(t)$$
$$\delta_{i,G} = 1 - \delta_{i,j}$$

Proposed CUD Approach Flowchart

- **Initial Phase (a):**
  - CCS assesses GBS load and surplus users
  - All user associated with GBS coverage
- **Re-association Phase (b):**
  - Re-association of excess users to UAVr
- **User Association and Power Optimization (c)**:
  - Repeat phases for each excess user
  - Update final parameters for UAVr to adjust associations and power

▲ GBS ▲ UAVr ● User ↖ User Association Direction



Performance Schemes

1. **Cooperative UAVr Deployment (CUD) Framework:**
   - Combines received signals with maximum weights.

$$\gamma^{\mathrm{MRC}} = \overbrace{\gamma_{i,s}}^{\text{Direct signal}} + \overbrace{\frac{\gamma_{j,s} \cdot \gamma_{i,j}}{\gamma_{i,j} + \varsigma}}^{\text{Cooperative signal}}$$

2. **Equal Gain Combining-SAGIN (EGC-SAGIN):**
   - Combines multiple received signals with equal weights.

$$\gamma^{\mathrm{EGC}} = \frac{\left(\gamma_{i,s} + \frac{\gamma_{j,s} \cdot \gamma_{i,j}}{\gamma_{i,j} + \varsigma}\right)}{2}$$

3. **LEO Satellite-GBS (LEO-GBS):**
   - No relay present, Only LEO satellite and GBS are in service.

$$\gamma^{\mathrm{LEO}} = \gamma_{i,s}$$

4. **Ground Base Station (GBS-only):**
   - No additional support present

$$\gamma^{\mathrm{GBS}} = \gamma_{i,G}$$

Result Analysis

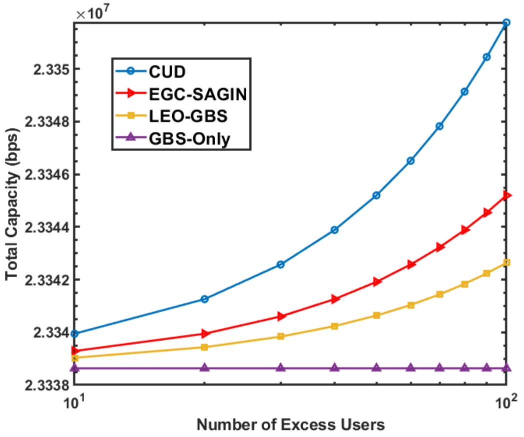
Superior Network Capacity and Energy Efficiency

Performance Overview:

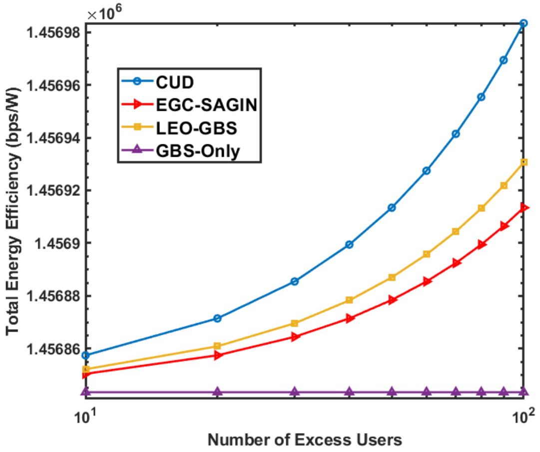
- The CUD framework outperforms GBS-only, EGC-SAGIN, and LEO-GBS in both network capacity and energy efficiency.

Key Advantages:

- Enhanced Capacity: Strategic UAVr deployment effectively manages excess user traffic, optimizing overall network capacity.
- Energy Efficiency: CUD provides significant energy savings compared to GBS-only and EGC-SAGIN, making it a greener alternative.
- Traffic Management: Proximity of UAVr to users improves traffic handling, preventing congestion and maximizing capacity.



(a) Total Capacity vs Number of Excess Users



(b) Total Energy Efficiency vs Number of Excess Users

CUD = Cooperative UAVr Deployment, EGC-SAGIN=Equal Gain Combining-SAGIN, LEO-GBS=LEO Satellite- Ground Base Station

- Proposed an cooperative UAVr Deployment (CUD) strategy for SAGINs.
- Utilizes UAVs as relays in an Amplify-and-Forward system to maximize SNR at the user.
- Adapts to fluctuating user traffic by: Deploying UAVr adaptively.
- Maximizing user SNR through intelligent, cooperative communication.
- Demonstrates significant improvements in:
    - Network capacity, Energy efficiency.
- Highlights the potential of integrating UAVs and LEO satellite-based technologies in future urban communication networks.

CUD = Cooperative UAVr Deployment, EGC-SAGIN=Equal Gain Combining-SAGIN, LEO-GBS=LEO Satellite- Ground Base Station

Thanks for Listening!

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Appendix

Instantaneous SNR at the user

$$\gamma_{\mathrm{AF}}(\mathrm{w}) = \frac{\mathrm{E}\left\{\left(\mathrm{w}^{\dagger}\mathrm{H}x_{\mathrm{sym}}\right)\left(\mathrm{w}^{\dagger}\mathrm{H}x_{\mathrm{sym}}\right)^{\dagger}\right\}}{\mathrm{E}\left\{\left(\mathrm{w}^{\dagger}\square\right)\left(\mathrm{w}^{\dagger}\square\right)^{\dagger}\right\}},$$

$$\textbf{Signal power} = \mathrm{E}\left\{\left(\mathrm{w}^{\dagger}\mathrm{H}x_{\mathrm{sym}}x_{\mathrm{sym}}{}^{\dagger}\mathrm{wH}\right)\right\} = \left(\mathrm{w}^{\dagger}\mathrm{H}\right)\mathrm{E}\underbrace{\left\{\left(x_{\mathrm{sym}}x_{\mathrm{sym}}{}^{\dagger}\right)\right\}}_{\text{Power}}\left(\mathrm{wH}^{\dagger}\right),$$

$$= P_s^{\mathrm{tx}}\left(\mathrm{w}^{\dagger}\mathrm{HH}^{\dagger}\mathrm{w}\right) = P_s^{\mathrm{tx}}\left(\mathrm{w}^{\dagger}R_k\mathrm{w}\right)$$

Similarly we can write,

$$\textbf{Noise power} = \mathrm{E}\left\{\left(\mathrm{w}^{\dagger}\square\right)\left(\mathrm{w}^{\dagger}\square\right)^{\dagger}\right\},$$

$$= \mathrm{E}\left\{\left(\mathrm{w}^{\dagger}\square\square^{\dagger}\mathrm{w}\right)\right\} = \mathrm{w}^{\dagger}\mathrm{E}\left\{\left(\square\square^{\dagger}\right)\right\}\mathrm{w},$$

$$= \mathrm{w}^{\dagger}R_{\mathrm{n}}\mathrm{W}$$

$$\gamma_{\mathrm{AF}}(\mathrm{w}) = P_s^{\mathrm{tx}}\left(\frac{\mathrm{w}^{\dagger}R_k\mathrm{w}}{\mathrm{w}^{\dagger}R_{\mathrm{n}}\mathrm{w}}\right),$$

Dual hop Cooperative Communication

- Receive beamformer $\boldsymbol{w}^{\dagger}$ at user is:

$$\mathrm{w}^{\dagger}(r_s^{\mathrm{Tot}}) = \mathrm{w}^{\dagger}(\mathbb{H}x_{\mathrm{sym}} + \mathbb{N}) = \underbrace{\mathrm{w}^{\dagger}\mathbb{H}x_{\mathrm{sym}}}_{\mathrm{Signal}} + \underbrace{\mathrm{w}^{\dagger}\mathbb{N}}_{\mathrm{Noise}}$$

- The instantaneous weighted SNR at the user is:

$$\gamma_{\mathrm{AF}}(\mathrm{w}) = \frac{\mathrm{Signal}}{\mathrm{Noise}} = P_s^{\mathrm{tx}}.\frac{\mathrm{w}^{\dagger}\mathbb{H}\mathbb{H}^{\dagger}\mathrm{w}}{\mathrm{w}^{\dagger}R_n\mathrm{w}} \ldots \ldots\ldots\ldots\ldots\ldots(1)$$

- After differentiating (γ_{AF}) (1) with respect to 'w' and set ($\frac{\partial}{\partial \mathrm{w}}\gamma_{\mathrm{AF}}$=0)[1]:

$$\mathrm{w}_{\mathrm{opt}} = c_r \,.\, R_n^{-1}\,\mathbb{H}$$

→ *Optimal weight*

- Now the maximum SNR after amplify and forward (AF) defined as:

$$\gamma_{\mathrm{AF},max}^{\mathrm{WCD}} = P_s^{\mathrm{tx}}\mathbb{H}^{\dagger}R_n^{-1}\mathbb{H} = \gamma_{i,s} + \frac{\gamma_{j,s}\gamma_{i,j}}{\gamma_{i,j} + \varsigma}$$

$(.)^{\dagger}$ =conjugate transpose, WCD = weighted cooperative diversity

- $r_s^{\mathrm{Tot}} = \mathbb{H}x_{\mathrm{sym}} + \mathbb{N}$

where $r_s^{\mathrm{Tot}} = \begin{bmatrix} r_s^{i,s} \\ r_s^{i,j} \end{bmatrix}$, $\mathbb{H} = \begin{bmatrix} h_0 \\ h_2 g h_1 \end{bmatrix}$, $\mathbb{N} = \begin{bmatrix} n_0 \\ h_2 g n_1 + n_2 \end{bmatrix}$, x_{sym}= satellite Transmit Power,

- $P_s^{\mathrm{tx}} = \mathbb{E}\{x_{\mathrm{sym}}x_{\mathrm{sym}}^{\dagger}\}$
- $R_n = \mathbb{E}\{\mathbb{N}\mathbb{N}^{\dagger}\}$
- c_r= Arbitrary Constant
- $\gamma_{i,j}$=UAVr to user SNR
- $\gamma_{j,s}$=Satellite to UAVr SNR
- $\gamma_{i,s}$=Satellite to user SNR
- $\varsigma = \frac{1}{\sigma^2 g^2}$
- g- Fixed Gain

[1] B. Holter and G. E. Oien, "The optimal weights of a maximum ratio combiner using an Eigen filter approach," in *5th Nordic Signal Processing Symposium*. Citeseer, 2002.

Channel Model: UAVr to User

- Considering LOS and NLOS path loss [1]:

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

$$PL^{\mathrm{NLoS}}_{d_{i,j}}(t) = 20\log_{10}\left(\frac{4\pi f_c d_{i,j}(t)}{c}\right) + \eta_{\mathrm{NLoS}}$$

- Probability of LOS and NLOS signal:

$$P^{\mathrm{LoS}}_{d_{i,j}}(t) = \frac{1}{1 + a\exp\left(-b\left[\frac{180}{\pi}\theta_{\mathrm{i,j}} - a\right]\right)}, \quad \& \quad P^{\mathrm{NLoS}}_{d_{i,j}}(t) = 1 - P^{\mathrm{LoS}}_{d_{i,j}}(t).$$

- The average path loss:

$$PL^{\mathrm{Avg}}_{d_{i,j}}(t) = P^{\mathrm{LoS}}_{d_{i,j}}(t) \times PL^{\mathrm{LoS}}_{d_{i,j}}(t) + P^{\mathrm{NLoS}}_{d_{i,j}}(t) \times PL^{\mathrm{NLoS}}_{d_{i,j}}(t)$$

$$= \frac{\eta_{\mathrm{LoS}} - \eta_{\mathrm{NLoS}}}{1 + a\exp\left(-b\left[\frac{180}{\pi}\theta_{\mathrm{i,j}} - a\right]\right)} + 20\log_{10}\left(d_{i,j}(t)\right) + \beta$$

where $\beta = 20\log_{10}\left(\frac{4\pi f_c}{c}\right) + \eta_{\mathrm{NLoS}}$

- SNR for User associated with UAVr

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

where $p_{i,j}$ minimum transmission power of UAVr

- Total power: Communication and UAVr Hover

$$p_j^{\mathrm{Tot}}(t) = p_{i,j}(\mathrm{t}) + p_j^{\mathrm{Hov}}(t)$$

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[1] A. Al-Hourani *et al.*, “Optimal LAP altitude for maximum coverage,” *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 569–572, 2014.

Constraints

1. UAVr power limitation

$$0 \le p_{i,j} \le p_{\max}$$

$p_{i,j}$: UAVr transmission power, $p_{\max}$: max UAVr transmission power

Remark: UAVr transmission power must satisfy the condition

2. UAVr user association limitation

$$0 \le |\Omega_j| \le \omega_j^{\max}$$

Ω_j: user set associated with UAVr, $\omega_j^{\max}$:max users association capacity of UAVr

Remark: UAVr user association must satisfy the condition

3. GBS user association limitation

$$0 \le |\Omega_G| \le \omega_G^{\max}$$

Ω_G: user set associated with GBS, $\omega_G^{\max}$: max user association capacity of GBS

Remark: GBS user association must satisfy the condition

4. User coverage limitations

$$r_{i,j}^2 \le R_j^2(t)$$

$r_{i,j}$:user distance from the center of the UAVr coverage, R_j: denoted the UAVr coverage radius

Remark: user under UAVr coverage must satisfy condition

5. User association limitations

$$\delta_{i,G} = 1 - \delta_{i,j}$$

Remark: user, $\delta_{i,G}$= 1 indicates GBS association, while $\delta_{i,j}$= 1 indicates UAVr association.

Simulation Parameters

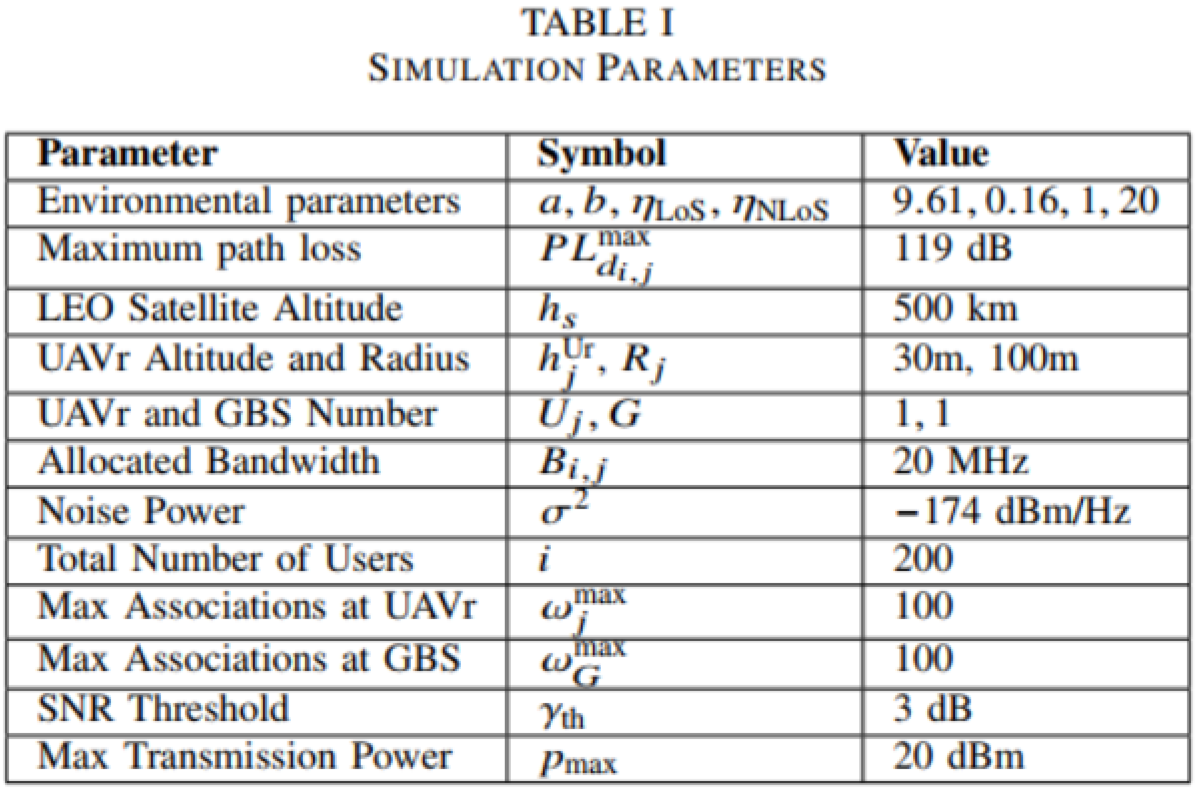

TABLE I
SIMULATION PARAMETERS

Parameter	**Symbol**	**Value**
Environmental parameters	$a, b, \eta_{\mathrm{LoS}}, \eta_{\mathrm{NLoS}}$	$9.61, 0.16, 1, 20$
Maximum path loss	$PL_{d_{i,j}}^{\mathrm{max}}$	119 dB
LEO Satellite Altitude	h_s	500 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	ω_j^{max}	100
Max Associations at GBS	ω_G^{max}	100
SNR Threshold	γ_{th}	3 dB
Max Transmission Power	p_{max}	20 dBm

Phase Synchronization

- The satellite simultaneously transmits a signal to the UAV-R and the UE in Phase I.
- The UAV-R node then re-transmits the satellite signal to the UE in Phase II while satellite s remains silent.
- When node UE receives various copies of the same signal in two phases, it combines them using the CUD approach.
- Since UAV-R time division multiple access (TDMA), the phase I to phase II. Thus, to complete the transmission of a frame from satellite s to UE, t+1 time slots are required.
- In addition, assuming no information exchange occurs between UAV-R nodes operating in a time division duplex mode, the signals transmitted by satellite nodes and UAV-R are perfectly synchronized at node UE [1].

[1] Y. Zhao, H. Chen, L. Xie, and K. Wang, “Exact and asymptotic ergodic capacity analysis of the hybrid satellite-terrestrial cooperative system over generalized fading channels,” *IET Communications*, vol. 12, no. 11, pp. 1342–1350, 2018.