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Resource Allocation for Solar Powered UAV Communication Systems

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Introduction

- Unmanned aerial vehicle (UAV) communication systems facilitate fast and flexible deployment due to their excellent maneuverability.
- Existing UAV communication systems cannot guarantee stable and sustainable communication services due to the limited energy storage.
- Solar powered UAV has potential to realize perpetual flight and enable sustainable communications.
- There is a fundamental tradeoff between harvesting solar energy and improving communication performance.
- **Main contribution**: Suboptimal algorithm design for joint 3-D positioning, power and subcarrier allocation of solar powered multicarrier UAV systems.

System Model

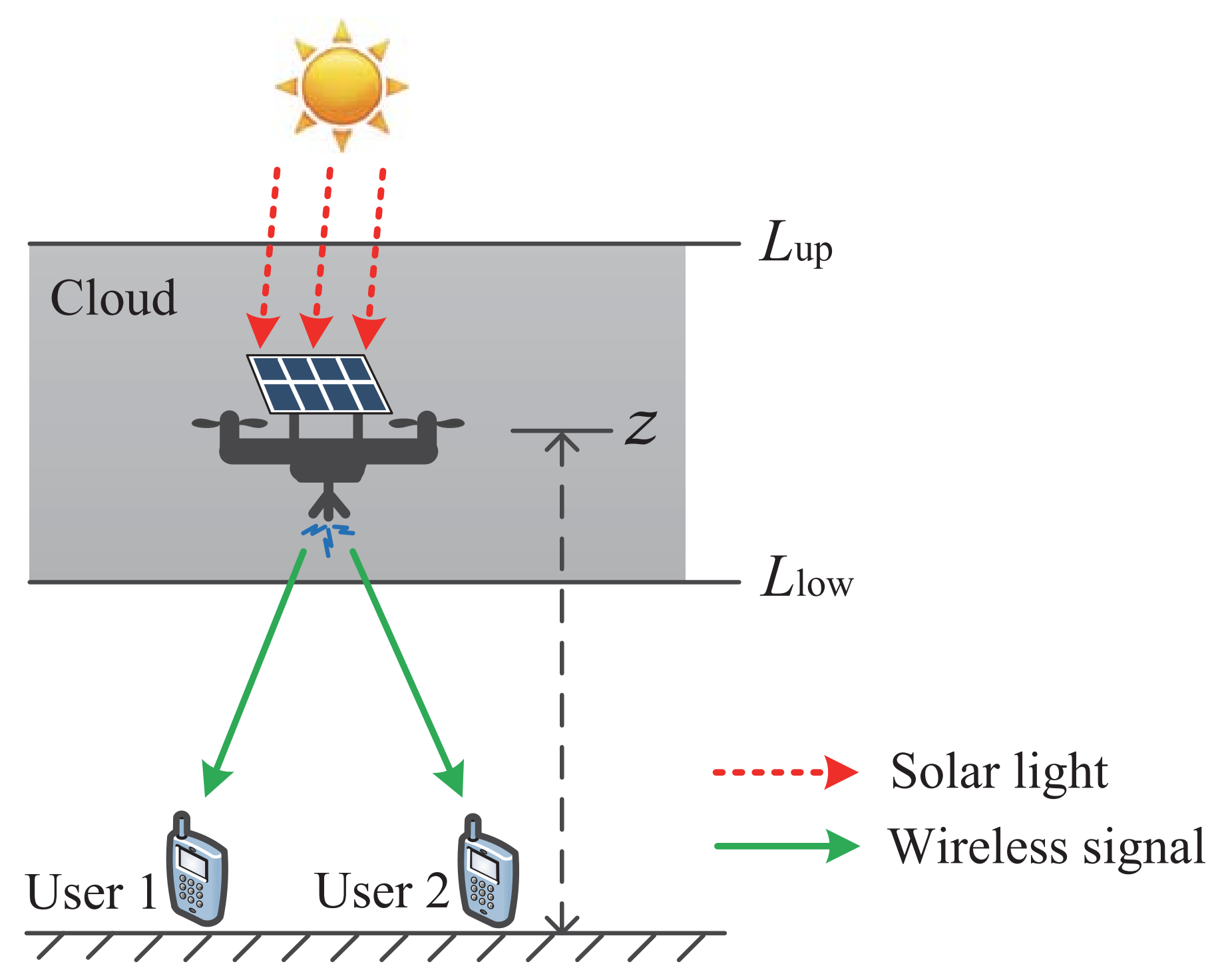

Fig. 1. A solar powered multicarrier UAV communication system with one UAV transmitter and $K = 2$ downlink users.

A. Channel Model

Received signal at DL user k on subcarrier i is given by

$$u_k^i = \frac{\sqrt{\varrho p_k^i}\,h_k^i}{\|\mathbf{r}-\mathbf{r}_k\|}d_k^i + n_k^i, \qquad (1)$$

- $\mathbf{r} = (x, y, z)$: 3-D coordinates of the UAV
- $\mathbf{r}_k = (x_k, y_k, 0)$: 3-D coordinates of user k
- p_k^i : transmit power to user k on subcarrier i
- h_k^i : DL channel to user k on subcarrier i
- d_k^i : DL transmitted data symbol
- ϱ : path loss parameter
- $n_k^i \sim \mathcal{CN}(0, \sigma_k^2)$: AWGN at DL users

B. Solar Energy Harvesting

The atmospheric transmittance at altitude z can be empirically approximated as follows:

$$\varphi(z) = \alpha - \beta e^{-z/\delta}. \qquad (2)$$

- α : the maximum value of the atmospheric transmittance
- β : the extinction coefficient of the atmosphere
- δ : the scale height of the earth

The attenuation of solar light passing through a cloud can be modeled as:

$$\varphi(d^{\mathrm{cloud}}) = e^{-\beta_c d^{\mathrm{cloud}}}. \qquad (3)$$

- $\beta_c \geq 0$: the absorption coefficient of clouds, modeling optical characteristics
- d^{cloud} : the distance that the solar light propagates through the cloud

Therefore, the electrical output power of the solar panels at altitude z is modeled as:

$$\begin{aligned} &P^{\mathrm{solar}}(z)\\ =&\begin{cases}\eta SG\varphi(z)\varphi(0), & z \geq L_{\mathrm{up}}\\ \eta SG\varphi(z)\varphi(L_{\mathrm{up}}-z), & L_{\mathrm{low}} \leq z < L_{\mathrm{up}}\\ \eta SG\varphi(z)\varphi(L_{\mathrm{up}}-L_{\mathrm{low}}), & z < L_{\mathrm{low}}\end{cases}\\ =&\begin{cases}A - Be^{-z/\delta}, & z \geq L_{\mathrm{up}}\\ M(z) - BC_1e^{(\beta_c-1/\delta)z}, & L_{\mathrm{low}} \leq z < L_{\mathrm{up}}\\ AC_2 - BC_2e^{-z/\delta}, & z < L_{\mathrm{low}}\end{cases}\end{aligned}$$

- A, B, C_1, C_2 are constants
- $M(z) = AC_1e^{\beta_c z}$
- η : the energy harvesting efficiency
- S : the area of the solar panels
- G : the average solar radiation on earth
- L_{up} and L_{low} : the altitudes of the upper and lower boundaries of the cloud

Optimization Problem Formulation

Maximization of the system sum throughput in each time slot:

$$\begin{aligned} \underset{s_k^i, p_k^i, \mathbf{r}}{\text{maximize}}\quad & \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K} s_k^i \log_2\left(1 + \frac{H_k^i p_k^i}{\|\mathbf{r}-\mathbf{r}_k\|^2}\right) \qquad (4)\\ \text{s.t.}\quad & \text{C1: } \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K} s_k^i p_k^i + P_{\mathrm{UAV}} \leq P^{\mathrm{solar}}(z), \quad \text{C2: } p_k^i \geq 0, \forall i, k,\\ & \text{C3: } \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K} s_k^i p_k^i \leq P_{\max}, \quad \text{C4: } z_{\min} \leq z \leq z_{\max},\\ & \text{C5: } s_k^i \in \{0, 1\}, \forall i, k, \quad \text{C6: } \sum_{k=1}^{K} s_k^i \leq 1, \forall i. \end{aligned}$$

- $H_k^i = \varrho |h_k^i|^2/\sigma_k^2$ and $s_k^i \in \{0, 1\}$ is the binary subcarrier indicator
- P_{UAV} : the power required for maintaining the operation of the UAV
- $P_{\max}$: the maximum transmit power at the UAV

Optimization Problem Solution

A. Handling of Binary Subcarrier Indicator

Define $\tilde{p}_k^i = s_k^i p_k^i$ and absorb the binary subcarrier indicator into the objective function:

$$\begin{aligned} \underset{\tilde{\mathbf{p}}, \mathbf{r}}{\text{maximize}}\quad & \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K} \log_2\left(1 + \frac{\frac{H_k^i}{\|\mathbf{r}-\mathbf{r}_k\|^2}\tilde{p}_k^i}{\frac{H_k^i}{\|\mathbf{r}-\mathbf{r}_k\|^2}\sum_{m\neq k}^{K}\tilde{p}_m^i + 1}\right) \qquad (5)\\ \text{s.t.}\quad & \widetilde{\text{C1}}\text{: } \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K}\tilde{p}_k^i + P_{\mathrm{UAV}} \leq P^{\mathrm{solar}}(z), \quad \widetilde{\text{C2}}\text{: } \tilde{p}_k^i \geq 0, \ \forall i, k, \quad \widetilde{\text{C3}}\text{: } \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K}\tilde{p}_k^i \leq P_{\max}, \quad \text{C4}, \end{aligned}$$

where $\frac{H_k^i}{\|\mathbf{r}-\mathbf{r}_k\|^2}\sum_{m\neq k}^{K}\tilde{p}_m^i$ represents the multiuser interference at user k from the $K-1$ co-channel users.

Theorem 1 *The optimal subcarrier assignment strategy for maximizing the system sum throughput in* (5) *assigns each subcarrier to the user with the best channel gain and no subcarrier is shared by multiple users.*

B. Handling of Quadratic Path Loss Term

Introduce an auxiliary variable θ_k:

$$\begin{aligned} \underset{\tilde{\mathbf{p}}, \mathbf{r}, \boldsymbol{\theta}}{\text{maximize}}\quad & \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K} \log_2\left(1 + \frac{H_k^i\tilde{p}_k^i}{\sum_{m\neq k}^{K} H_k^i\tilde{p}_m^i + \theta_k}\right) \qquad (6)\\ \text{s.t.}\quad & \widetilde{\text{C1}}\text{–}\widetilde{\text{C3}}, \text{C4}, \quad \text{C7: } \|\mathbf{r}-\mathbf{r}_k\|^2 \leq \theta_k. \end{aligned}$$

Rewrite the problem (6) as a difference of convex (D.C.) programming problem:

$$\begin{aligned} \underset{\tilde{\mathbf{p}}, \mathbf{r}, \boldsymbol{\theta}}{\text{minimize}}\quad & -\sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K} \log_2\left(\sum_{m=1}^{K} H_k^i\tilde{p}_m^i + \theta_k\right) - \left(-\sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K} \log_2\left(\sum_{m\neq k}^{K} H_k^i\tilde{p}_m^i + \theta_k\right)\right)\\ \text{s.t.}\quad & \widetilde{\text{C2}}, \widetilde{\text{C3}}, \text{C4}, \text{C7}, \quad \widetilde{\text{C1}}\text{: } \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K}\tilde{p}_k^i + P_{\mathrm{UAV}} \leq P^{\mathrm{solar}}(z), \qquad (7) \end{aligned}$$

and define $G(\tilde{\mathbf{p}}, \boldsymbol{\theta}) = -\sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K}\log_2\left(\sum_{m\neq k}^{K} H_k^i\tilde{p}_m^i + \theta_k\right)$.

D. Successive Convex Approximation

Then, for any given $\tilde{\mathbf{p}}^{(j)}$ and $\boldsymbol{\theta}^{(j)}$, we can obtain a lower bound for (7) by solving the following optimization problem:

$$\begin{aligned} \underset{\tilde{\mathbf{p}}, \mathbf{r}, \boldsymbol{\theta}}{\text{minimize}}\quad & -\sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K} \log_2\left(\sum_{m=1}^{K} H_k^i\tilde{p}_m^i + \theta_k\right) - \underline{G}(\tilde{\mathbf{p}}, \boldsymbol{\theta}, \tilde{\mathbf{p}}^{(j)}, \boldsymbol{\theta}^{(j)}) \qquad (8)\\ \text{s.t.}\quad & \widetilde{\text{C2}}, \widetilde{\text{C3}}, \text{C4}, \text{C7}, \quad \widetilde{\text{C1}}\text{: } \sum_{i=1}^{N_{\mathrm{F}}}\sum_{k=1}^{K}\tilde{p}_k^i + P_{\mathrm{UAV}} \leq \underline{P}^{\mathrm{solar}}(z), \end{aligned}$$

where $\underline{G}(\tilde{\mathbf{p}}, \boldsymbol{\theta}, \tilde{\mathbf{p}}^{(j)}, \boldsymbol{\theta}^{(j)}) = G(\tilde{\mathbf{p}}^{(j)}, \boldsymbol{\theta}^{(j)}) + \nabla_{\tilde{\mathbf{p}}}G(\tilde{\mathbf{p}}, \boldsymbol{\theta})(\tilde{\mathbf{p}} - \tilde{\mathbf{p}}^{(j)}) + \nabla_{\boldsymbol{\theta}}G(\tilde{\mathbf{p}}, \boldsymbol{\theta})(\boldsymbol{\theta} - \boldsymbol{\theta}^{(j)})$ and $\underline{P}^{\mathrm{solar}}(z)$ are the global underestimations of $G(\tilde{\mathbf{p}}, \boldsymbol{\theta})$ and $P^{\mathrm{solar}}(z)$, respectively.

Simulation Results

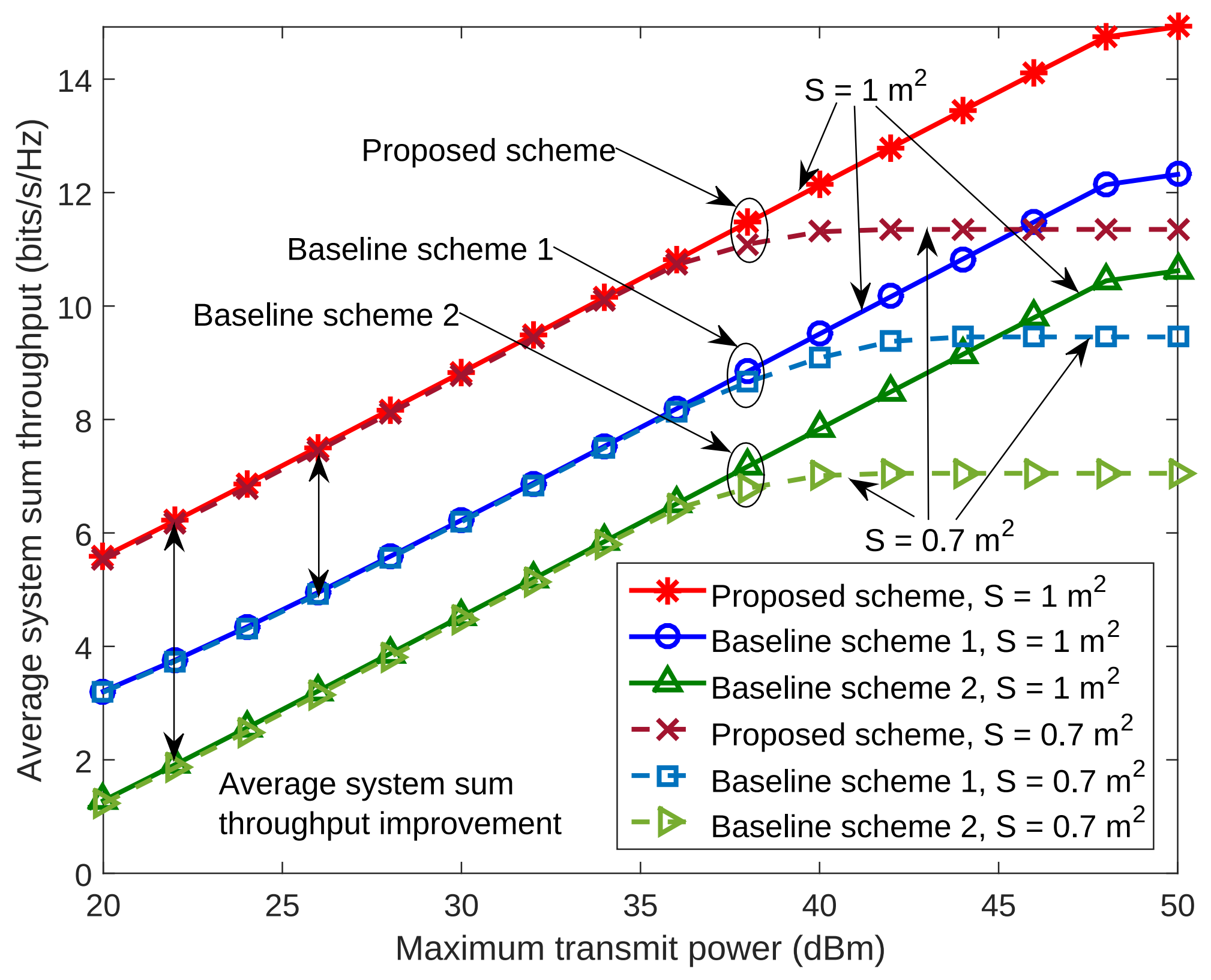

Fig. 2. Average system sum throughput (bits/s/Hz) versus the maximum transmit power of the UAV (dBm), $P_{\max}$, for different resource allocation schemes and $K = 3$ users.

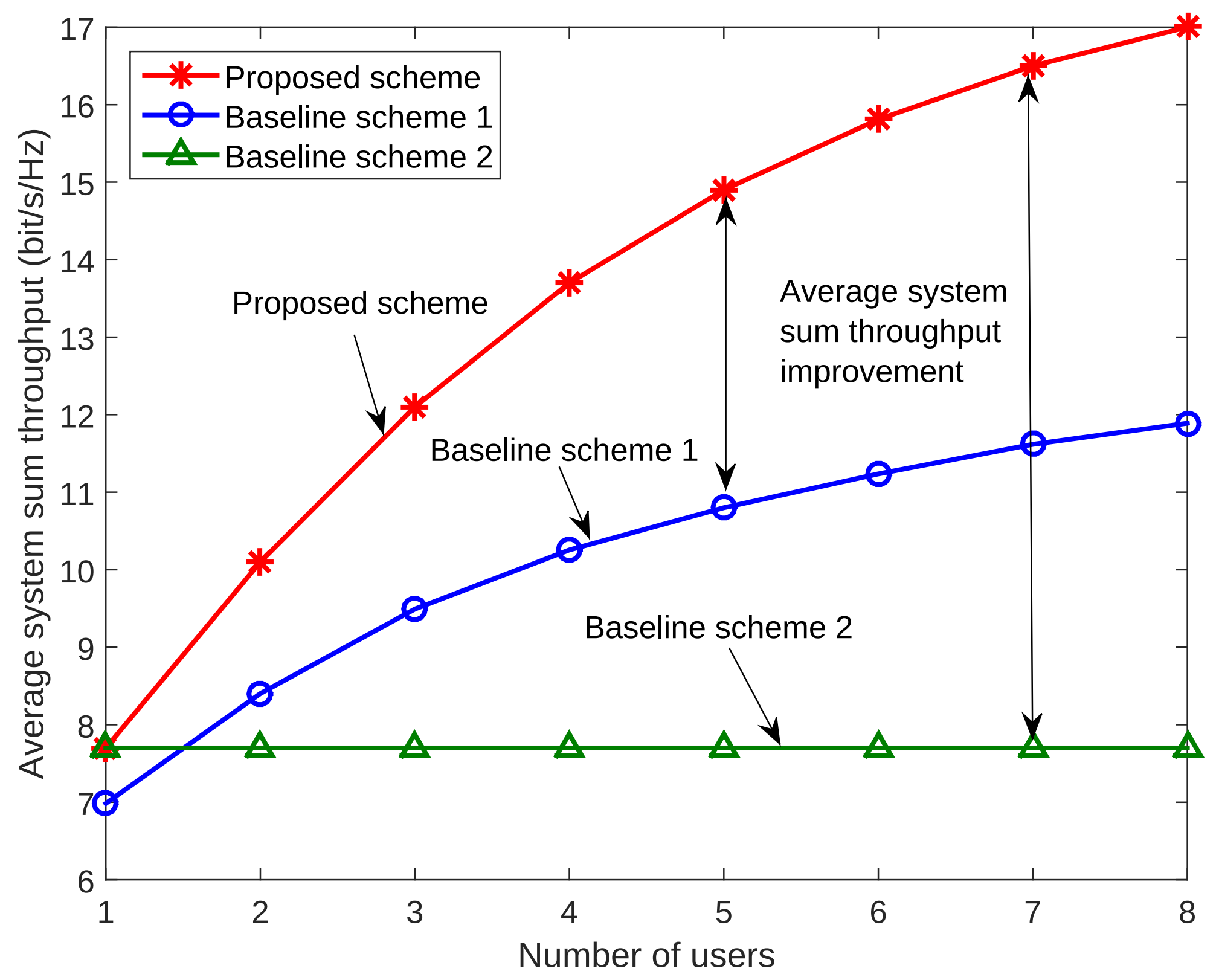

Fig. 3. Average system sum throughput (bits/s/Hz) versus the number of users for different resource allocation schemes with $P_{\max} = 40$ dBm and $S = 1$ m^2 solar panels.

Reference

[1] Y. Zeng, R. Zhang and T. J. Lim, “Wireless Communications with Unmanned Aerial Vehicles: Opportunities and Challenges,” *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36-42, May 2016.

[2] Q. Wu, Y. Zeng, and R. Zhang, “Joint Trajectory and Communication Design for Multi-UAV Enabled Wireless Networks,” *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, March 2018.