Efficient UAV Hovering, Resource Allocation, and Trajectory Design for ISAC with Limited Backhaul Capacity

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Abstract

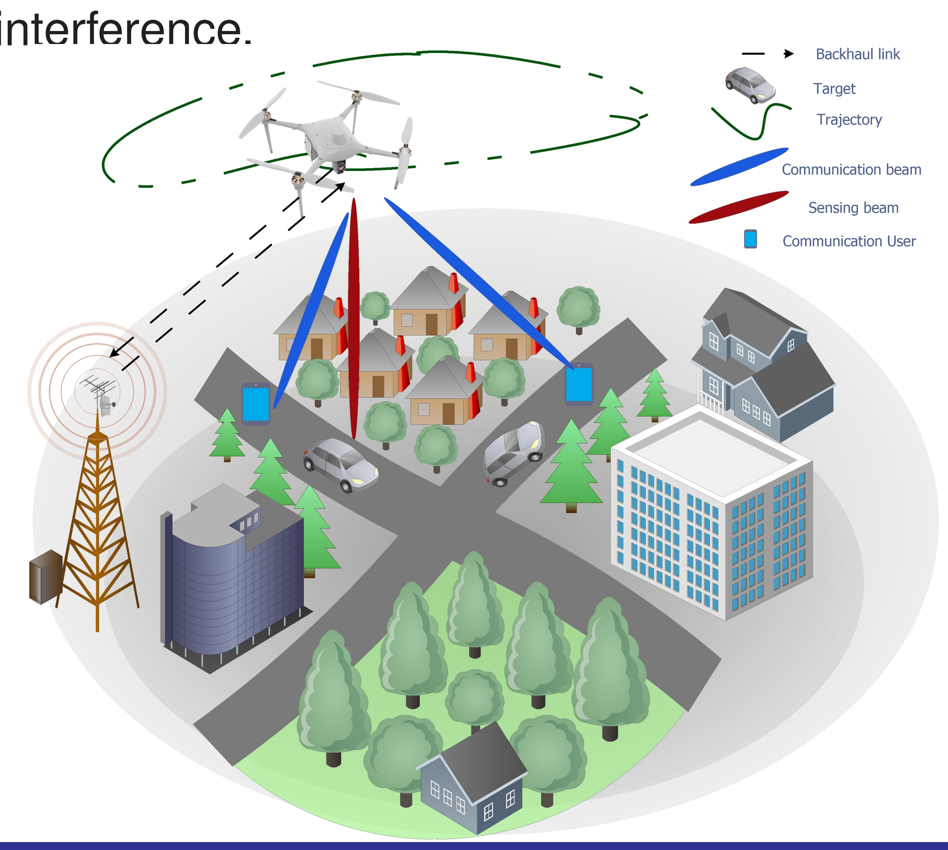
- We propose a novel joint resource allocation and trajectory design for UAV-enabled ISAC systems.
- The UAV hovers above targets to perform high-quality sensing.
- Acquired sensing data is offloaded to a ground base station with limited backhaul capacity for further processing.
- Radar-based sensing is used in orthogonal time slots to avoid interference with communication.
- Simulation results demonstrate significant power savings, optimized UAV trajectories, and efficient sensing data management compared to baseline methods.

Introduction and Motivation

- **ISAC** is critical for emerging 6G networks, aiming to improve spectrum efficiency and enable seamless physical infrastructure sharing.
- **UAV-enabled ISAC Systems** provide flexibility in deployment, enabling line-of-sight (LoS) links for both communication and sensing, which is crucial for high-precision applications.
- UAVs can **hover** to perform high-quality sensing, focusing on specific targets, and can adjust their trajectory and resource allocation to minimize power consumption while meeting QoS requirements.
- **Offloading sensing data** to a ground base station allows for reduced computational burden on the UAV and efficient processing with limited backhaul capacity.
- By utilizing **radar-based sensing in orthogonal time slots**, the system prevents interference between communication and sensing tasks, achieving reliable performance in both domains.

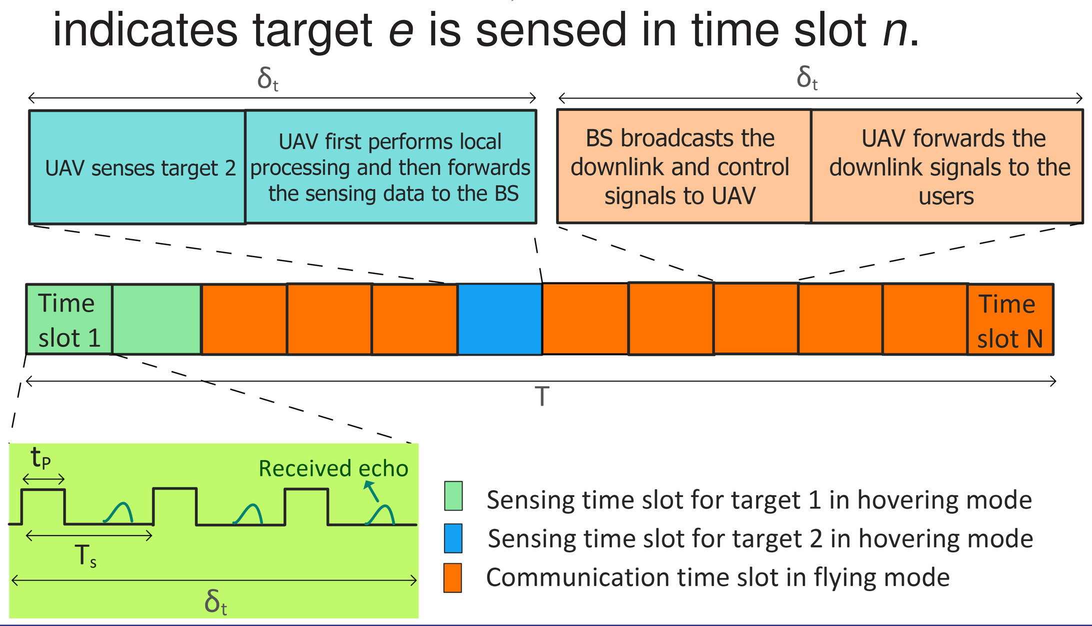
System Model

- **UAV-ISAC Framework**: A rotary-wing UAV with M-antenna uniform linear array (ULA) serves K communication users and E sensing targets.
- **Operation**: The UAV alternates between communication and sensing modes over N time slots, hovering during sensing to ensure accurate data acquisition.
- γ_k: Received SINR at user k.
- Γ_e: Sensing SNR of target e.
- **Orthogonal Time Slots**: Sensing and communication occur in separate time slots to avoid interference.



ISAC Frame Structure

- **Orthogonal Time Slots**: Sensing and communication are performed in separate time slots to avoid interference.
- **Sensing During Hovering**: The UAV hovers over each target to improve sensing accuracy and reduce Doppler effects, focusing the beam on one target at a time.
- **Sensing Indicator** $\alpha_{e,n}$: Controls the scheduling of sensing, where $\alpha_{e,n} = 1$ indicates target e is sensed in time slot n.



Problem Formulation

Objective: Optimize trajectory, velocity, and power allocation to minimize energy consumption while meeting quality of service (QoS) requirements for sensing and communication.

Communication constraints, Sensing constraints, UAV Trajectory constraints

Problem Formulation

$$\mathcal{P}_1: \min_{\Xi} Obj \triangleq \frac{1}{N}\sum_{n=1}^{N}\Big(\eta\big(\sum_{k=1}^{K}\|\mathbf{w}_k[n]\|^2 + N_s\frac{t_p}{\delta_t}\mathrm{Tr}(\mathbf{R}[n])\big)+ P_{\text{aero}}(\mathbf{v}[n]) + M\,P_{\text{static}} + \sum_{e=1}^{E}\alpha_{e,n}\mathcal{P}_{\text{Loc}}[n] + \sum_{e=1}^{E}\alpha_{e,n}p^{\text{Off}}[n]\Big) \quad (1)$$

$$\text{s.t. C1}: \Big(1-\sum_{e=1}^{E}\alpha_{e,n}\Big)\sum_{k=1}^{K}\|\mathbf{w}_k[n]\|^2 + \sum_{e=1}^{E}\alpha_{e,n}N_s\frac{t_p}{\delta_t}\mathrm{Tr}(\mathbf{R}[n]) + \sum_{e=1}^{E}\alpha_{e,n}p^{\text{Off}}[n] \le P_{\max},$$

$$\text{C2}: \frac{1}{N}\sum_{n=1}^{N}\Big(1-\sum_{e=1}^{E}\alpha_{e,n}\Big)\log_2(1+\gamma_k[n]) \ge R^k_{\min}, \forall k,$$

$$\text{C3}: \sum_{n=1}^{N}\alpha_{e,n}\frac{\vartheta_e\beta_0^2\mathbf{a}^H(\theta_e)N_s\frac{t_p}{\delta_t}\mathbf{R}[n]\mathbf{a}(\theta_e)}{16\pi\Psi_e^4[n]\sigma_e^2} \ge \mathrm{SNR}_e^{\text{th}}, \forall e,$$

$$\text{C4}: R_{\text{U-B}}[n] \ge \alpha_{e,n}\iota R_{\text{Pr}},\ \forall e,n,\ \ \text{C5}: R_{\text{B-U}}[n] \ge \sum_{k=1}^{K}R^k_{\min}\Big(1-\sum_{e=1}^{E}\alpha_{e,n}\Big),\ \forall n,$$

$$\text{C6}: \sum_{e=1}^{E}\alpha_{e,n} \le 1, \forall n,\ \ \text{C7}: \sum_{n=1}^{N}\alpha_{e,n} \le N_s^{\max}, \forall e,$$

$$\text{C8}: \mathbf{q}[n+1]-\mathbf{q}[n] = \Big(1-\sum_{e=1}^{E}\alpha_{e,n}\Big)\mathbf{v}[n]\delta_t, \forall n,\ \ \text{C9}: \big\|\mathbf{v}[n+1]-\mathbf{v}[n]\big\| \le a_{\max}\delta_t,$$

$$\text{C10}: \big\|\mathbf{v}[n]\big\| \le \Big(1-\sum_{e=1}^{E}\alpha_{e,n}\Big)v_{\max},\ \text{C11}: \alpha_{e,n}\in\{0,1\},\ \text{C12}: \alpha_{e,n}\big\|\mathbf{q}[n]-\mathbf{d}_e\big\|^2 = 0,$$

$$\Xi \triangleq \{\mathbf{w}_k[n], p^{\text{Rad}}[n], p^{\text{Off}}[n], \alpha_{e,n}, \mathbf{q}[n], \mathbf{v}[n]\}.$$

Simulation Results

- **Baseline scheme 1**: We adopted a heuristic trajectory design for the UAV while optimizing the others.
- **Baseline scheme 2**: We adopted a zero-forcing beamforming for information transmission and a fixed velocity.

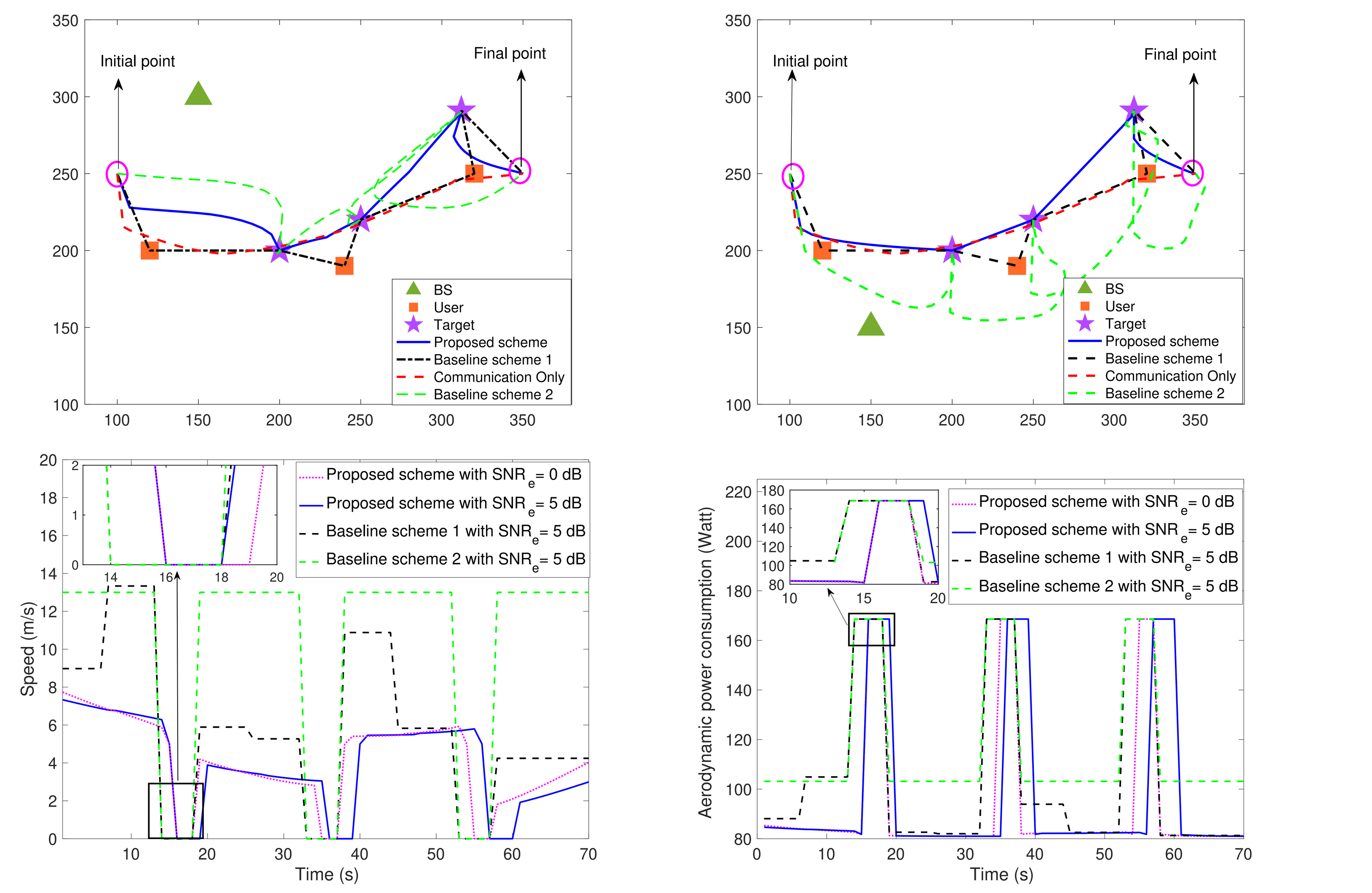


Figure 1: Trajectory, velocity, and aerodynamic power consumption of the UAV for different BS positions (a) and (b).

Conclusion

- We proposed a joint resource allocation and trajectory design framework for UAV-enabled ISAC with limited backhaul capacity, ensuring efficient data offloading and interference-free operation.
- **Radar-based sensing** was optimized for UAV hovering, with sensing and communication performed in **orthogonal time slots** to avoid interference.
- A low-complexity **AO-based algorithm** was developed, providing a high-quality suboptimal solution for the non-convex problem.
- Key findings:
  - **Significant power savings** compared to baseline schemes.
  - Trade-off: More stringent sensing requires **longer sensing times**.
  - The number of **sensing targets** impacts power consumption more than the number of communication users.
  - Larger **radar cross sections (RCS)** enable reduced radar power without losing sensing performance.
  - **Positioning the BS closer** to sensing targets improves data offloading.
  - **Optimized UAV trajectory** balances hovering for sensing and proximity to users/BS.

Reference

[1] A. Khalili, A. Rezaei, D. Xu, F. Dressler and R. Schober, "Efficient UAV Hovering, Resource Allocation, and Trajectory Design for ISAC with Limited Backhaul Capacity," in IEEE Transactions on Wireless Communications,