Mobility-Aware Resource Allocation in UAV-Assisted ISAC Networks

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In a dynamic environment with varying degrees of mobile ground users, optimizing the placement of UAVs are important in improving network throughput. Moreover, for integrated sensing and communication (ISAC) enabled UAV-BSs, the resource allocation for sensing and communication relies on the dynamic nature of the network environment. To keep track of the changes in the environment UAVs are required to continuously update their trajectory, the UAV trajectory update interval is also a crucial parameter that impacts the network performance; hence, characterizing the users' mobility level is an important tool to improve the UAV trajectory optimization. In this paper, we propose a mobility-aware resource allocation for joint sensing and communication. Our results demonstrate that the proposed algorithm can improve the resource allocation between sensing and communication in an ISAC-enabled UAV-assisted network.

***Index Terms*—UAV-assisted cellular communications, Integrated sensing and communications, wireless communication**

I. INTRODUCTION

In recent years, integrated sensing and communication (ISAC) enabled unmanned aerial vehicles (UAVs) have received a great deal of attention in the study of small-cell ultra-dense networks. Existing studies have focused on spectrum sharing for sensing and communication which bring with it some notable issues such as interference between sensing and communication radio, resource allocation, etc [1]. To address the issue of resource allocation and UAV placement optimization, current research has focused on investigating the communication-centric ISAC with a sensing-first-communicating-later approach [2]. These schemes employ hybrid analog and digital communication architecture by designing low-complexity and multi-beam algorithms, enabling the node to steer sensing and communication beams in different directions for simultaneously communicating and sensing functions.

Although UAV placement optimization has been studied for both static users [3], most environments are dynamic with varying degrees of user mobility. With the varying degrees of UE mobility, the resource allocation problem for sensing and communication becomes a challenge [4]. For instance, in [4], UAV locations are updated in accordance with the user locations over time in order to maximize the network throughput. It is imperative that for UAV-assisted communications, the network performance is impacted by user mobility. Therefore the direction of interest to be sensed and the time separation between two consecutive UAV placement intervals (trajectory optimization) must be determined based on the user mobility. However, this has not been considered in the prior literature.

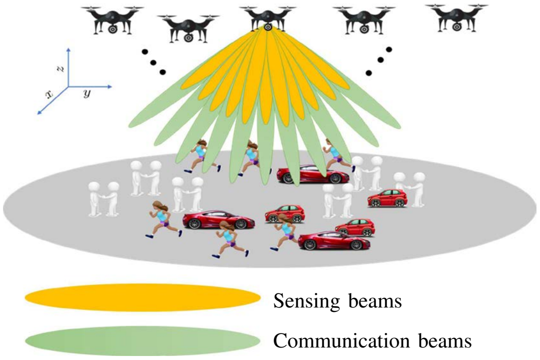

Fig. 1. Example scenario showing multiple UAVs and multiple UEs with varying degrees of mobility.

In this paper, we proposed a method to optimize the resource allocation for ISAC-enabled UAV-BS by characterizing the user's mobility level to reduce sensing overhead and improve the network throughput. In the proposed ISAC-enabled UAV-BS network, multiple users with varying degrees of mobility are deployed. Based on the sensed information, the direction of UE movement and the level of mobility, the UAV-UE association matrix and resource allocation are optimized.

II. SYSTEM MODEL

We consider a scenario where multiple K UEs and M UAVs are deployed as shown in Fig. 1. We assume that the UAVs are equipped with N_t uniform linear array antennas (ULA), while the UEs are equipped with a single antenna each. Furthermore, we assume that each UAV is equipped with an integrated sensing and communication module. The objective of this work is to optimize the sensing and communication resources subject to the users' mobility level.

A. Users Dynamics

For simplicity, consider a network consisting of users (UE) characterised by varying degrees of mobility (static or low-mobility level, mid-mobility level and high-mobility level) as shown in Fig 1. The state vector of the k-th UE at timestep n can be expressed as

$$\mathbf{x}_k[n] = [x_n^k, \dot{x}_n^k, \ddot{x}_n^k, y_n^k, \dot{y}_k^n, \ddot{y}_n^k, z, \dot{z}_n^k, \ddot{z}_n^k]^T, \tag{1}$$

where $x, \dot{x}, \ddot{x}$ denote the position, speed and acceleration in the x direction, which also holds for the y and z directions in (1). To account for the uncertainty in the UE mobility, the dynamic model of the UEs is composed of a command process vector $\boldsymbol{\nu}_k = [\nu_x^k, \nu_y^k, \nu_z^k]^T$ and a random acceleration vector $\boldsymbol{\omega}_k = [\omega_x^k, \omega_y^k, \omega_z^k]^T$, hence, the total acceleration is $\mathbf{a}_k = \boldsymbol{\omega}_k + \boldsymbol{\nu}_k$.

B. UAV Dynamics and Sensing

At timestep n, the state vector of the m-th UAV is represented by $\mathbf{u}_m^n = [u_x^m, u_y^m, u_z^m]^T$ where x, y and z are the coordinate vectors of the the UAVs. Let $\mathcal{S}$ be the set of ground users indices that need to be served by the UAVs In the n-th time step, the state vector of the m-th UAV can be expressed as

$$\mathbf{u}_m^n = \mathbf{u}_{m-1}^n + b_l = \mathbf{u}_{m-1}^n + \begin{bmatrix} \delta\cos(l\Delta_\theta) \\ \delta\sin(l\Delta_\theta) \\ h_l \end{bmatrix}, \tag{2}$$

where δ is a constant step distance that the UAVs can travel at each timestep n, $\Delta_\theta = 2\pi/N_\theta$ is the unit steering angle, b_l, for $l = \{1, \ldots, N_\theta\}$ is the action control along the x, y, and z axis and h_l is the discrete altitude. The UAV determine its trajectory by choosing its action from the discrete action space $\mathcal{B} \in \{b_1, b_2, \ldots b_{N_\theta}\}$. The channel model includes LoS and NLoS with a probability that depends on both the UAV's altitude and the elevation angle between the user and the UAV. Given the m-th UAV with an altitude h_m and the k-th user with a distance $r_{k,m}$ as shown in Fig. 1, the probability of LoS is given by [5]

$$p_{k,m}^{\text{LoS}}(r_{k,m}, d_{k,m}) = \frac{1}{1 + \epsilon \cdot \exp\left(-\beta \dfrac{180}{\pi} \arctan \dfrac{\sqrt{r_{k,m}^2 - d_{k,m}^2}}{d_{k,m}} - \epsilon\right)}, \tag{3}$$

where $d_{k,m}$ is the horizontal distance from the projected position of the UAV on the 2D plane, ϵ and β are environment-dependent parameters. Accordingly, the path loss between the m-th UAV and the k-th UE can be expressed as

$$L_{k,m}(r_{k,m}, d_{k,m}) = \left(\frac{4\pi f r_{k,m}}{c}\right)^{-\alpha} (\zeta_{LoS} p_{k,m}^{LoS}(r_{k,m}, d_{k,m}) + \zeta_{NLoS}(1 - p_{k,m}^{LoS}(r_{k,m}, d_{k,m}))^{-1}, \tag{4}$$

where ζ_{LoS} and ζ_{NLoS} represent the losses from the LoS and NLoS links respectively.

For traceability, we assume a fixed UAV altitude h_l which is sufficient to highlight the resource allocation problem. However, the problem can be extended to variable UAV heights.

C. Conventional Approach for Joint Sensing and Communication

Although there are several approaches to joint sensing and communication, a common approach is to allocate a specific band of frequency to the sensing radio while allocating a different frequency band for communication [2]. This can also be extended to the allocation of a portion of the time resource say ρ for sensing and $1 - \rho$ for communication as shown in Fig. 2. Using the beam split algorithm in [4], the beam from the m-th UAV in the direction of the k-th UE can be expressed as

$$\mathbf{f}_{m,k} = \sqrt{1-\rho}\,\mathbf{v}_{m,k} + \sqrt{\rho}\, e^{j\psi} \mathbf{u}_{m,n}, \tag{5}$$

where $\mathbf{v}_{m,k}$ is the analog beamformer for communicating with the k-th UE and $\mathbf{u}_{m,n}$ is the sensing beamformer in the n-th direction of interest. As observed from the conventional approach, Since the common sensing should serve all users in a cell, a large number of sensing beams is required to cover a wide range of directions. However, if users with varying mobility levels are considered in the network, the sensing has to be conducted more frequently, resulting in a substantial increase in the sensing resource.

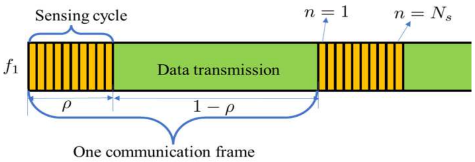

Fig. 2. Frame structure of the conventional ISAC-enabled system

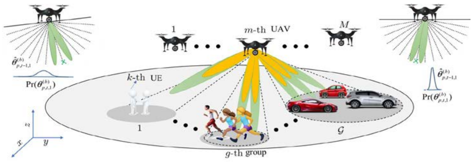

Fig. 3. Example scenario of proposed resource allocation based on users' mobility levels showing multiple UAVs and clusters of UEs.

III. PROPOSED USER MOBILITY LEVEL CHARACTERIZATION AND UAV-UES ASSOCIATION

To address the resource allocation for sensing and communication in users' mobility scenarios, we begin by characterizing the user's mobility level. Using the information from the user's mobility level, a UE-UAV association matrix $\mathbf{A} \in \mathbb{R}^{K \times M} = (a_{k,m})$ is designed to place UEs with the same mobility level and in the same direction of interest in a group. Using the information on the target users' group, the sensing resource can be efficiently allocated by employing only a small number of beams (dedicated beams) optimized for the specific group as shown in Fig. 3.

Due to the varying mobility of the UEs, the transition probability between the m-th UAV and the k-th UE can be evaluated as

$$T_{k,m}(x, y) = \frac{1}{C} \exp(-|\mathbf{x}_{k,m} - \mathbf{y}_{k,m}|^2 / \sigma_{k,m}^2), \tag{6}$$

where $\sigma_{k,m}$ indicates the mobility level of the k-th UE relative to the m-th UAV. Note that $\sigma_{k,m}$ can be obtained from the position information of the UE and UAV given by (1) and

TABLE I
SUMMARY OF SIMULATION PARAMETERS

Parameters	**Values**	**Parameters**	**Values**
Frame duration T	20 ms	Sampling time t_p	0.2 ms
Number of UEs per group K_g	5	Number of groups $\mathcal{G}$	3
SNR γ	-10 dB	Height of UAVs	15 m

(2). Based on the user's mobility level and the transition probability, the beam split ratio is updated to maximize the sum rate at each step time. In this paper, we focus on the impact of users' mobility level on the UAV update interval and evaluate the average sum rate for a given service area.

Consider the beam split in (5) for the joint sensing and communication at the m-th UAV where ρ is the beam split factor and ψ is the phase adjustment parameter. The signal-to-interference plus noise ratio of at the k-th UE can be expressed as

$$\gamma_{k,m}^{g} = \frac{\sqrt{\rho}|\mathbf{h}_{m,k}^{T}\mathbf{v}_{m,k}|^2}{\sqrt{\rho}\sum_{i=1,i\neq k}^{K}|\mathbf{h}_{m,k}^{T}\mathbf{v}_{m,i}|^2+\sqrt{1-\rho}|\mathbf{h}_{m,k}^{T}\mathbf{u}_{m,n}|^2+\sigma^2}. \quad (7)$$

The average sum rate can be expressed as

$$C_{k,m,g} = \sum_{g=1}^{\mathcal{G}}\sum_{m=1}^{M}\sum_{k=1}^{K} a_{k,m}b_{k,m}\mathbb{E}[\log_2(1+\gamma_{k,m}^{g})], \quad (8)$$

where $b_{k,m}$ is the allocated bandwidth from the m-th UAV to the k-th UE and $a_{k,m} \in \{0,1\}$ is the association index whose value is 1 if the m-th UAV is associated with the k-th UE and 0 otherwise.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we evaluate the performance of the proposed mobility-aware resource allocation scheme. The parameters used for the simulations are summarized in Tab. I. The users' mobility is classified into three mobility levels; low mobility (0-30 km/h), mid mobility (31-70 km/h) and high mobility (71-120 km/h).

In Fig. 4, the average update interval versus the number of UAVs is presented for varying user mobility levels. It can be observed that for low mobility levels, the update interval is less frequent compared to the mid and high mobility levels respectively. Hence, if the UAV update interval is not optimized for different mobility levels, the sensing resource cannot be efficiently allocated, consequently, the system throughput will be degraded.

The average sum rate for a given service area is presented in Fig. 5. The proposed mobility-aware resource allocation is applied for communication between the UAVs and the ground users. Although one would expect a geometrical increase in the average sum rate as the number of UAVs increases, this is not the case as shown by the figure. This is mainly due to the fact that as the number of UAVs increases, interference from the UAVs could be detrimental to the system's achievable rate. Furthermore, as the service area increases, the pathloss between the UAVs and the user could also impact the system's achievable sum rate. Overall, the proposed method is able to reduce the sensing overhead and thereby improve the resource allocation for communication.

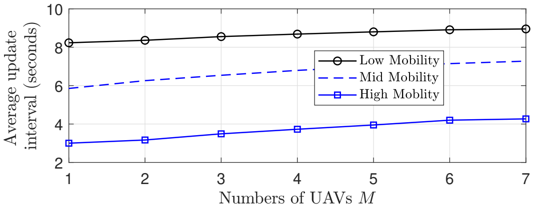

Fig. 4. Average update interval versus number of UAVs for different users' mobility level

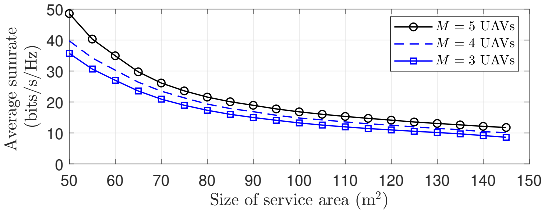

Fig. 5. Average total sum rate for a given service area

V. CONCLUSION

In this paper, we propose a mobility-aware resource allocation for UAV-enabled ISAC networks. From the numerical results, it is shown that users' mobility characterization can reduce sensing overhead and consequently enhance communication throughput. The proposed method allows for dedicated sensing towards groups of users with similar mobility levels thereby allowing for flexible UAV update interval based on the groups being served.

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REFERENCES

[1] K. Meng, Q. Wu, J. Xu, W. Chen, Z. Feng, R. Schober, and A. L. Swindlehurst, "UAV-enabled integrated sensing and communication: Opportunities and challenges," *IEEE Trans. Wireless Commun.*, pp. 1–9, 2023.

[2] J. Moon, S. Papaioannou, C. Laoudias, P. Kolios, and S. Kim, "Deep reinforcement learning multi-UAV trajectory control for target tracking," *IEEE Internet of Things J.*, vol. 8, no. 20, pp. 15 441–15 455, 2021.

[3] N. Nouri, F. Fazel, J. Abouei, and K. N. Plataniotis, "Multi-UAV placement and user association in uplink MIMO ultra-dense wireless networks," *IEEE Trans. on Mobile Comput.*, vol. 22, no. 3, pp. 1615–1632, 2023.

[4] H. Wang, H. Zhang, X. Liu, K. Long, and A. Nallanathan, "Joint UAV placement optimization, resource allocation, and computation offloading for THz band: A DRL approach," *IEEE Trans. Wireless Commun.*, vol. 22, no. 7, pp. 4890–4900, 2023.

[5] E. N. Almeida, A. Coelho, J. Ruela, R. Campos, and M. Ricardo, "Joint traffic-aware UAV placement and predictive routing for aerial networks," *Ad Hoc Netw.*, vol. 118, p. 102525, 2021.