



# ISAC-enable mobility-aware multi-UAV placement for ultra-dense networks

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## Abstract

This paper proposes a method for characterizing user mobility levels in multiple unmanned aerial vehicles (UAV)-assisted networks. In a dynamic environment with varying degrees of mobile ground users, optimizing the placement of UAVs is important in improving network throughput. Moreover, for integrated sensing and communication (ISAC) enabled UAVs, 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, hence, characterizing the users' mobility level is an important tool to improve the UAV trajectory optimization. In this paper, a mobility-aware resource allocation for joint sensing and communication is proposed. Our results demonstrate that the proposed algorithm can improve the resource allocation between sensing and communication in an ISAC-enabled UAV-assisted network.

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**Keywords:** 6G; Mobility aware; Integrated sensing and communication (ISAC); Unmanned aerial vehicle; Ultra-dense

## 1. 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 brings with it some notable issues such as interference between sensing and communication radio, resource allocation, etc [2]. To address the issue of resource allocation and UAV placement optimization, current research has focused on studying a communication-centric ISAC network with a sensing-first-communicating-later approach [3]. Such an approach employs a hybrid of analog and digital communication networks by applying low-complexity and multiple-beam algorithms. These allow the transmitter to steer the sensing beam in one direction and the communication beams in different directions for simultaneous communication and sensing functions [4].

Although UAV placement optimization has been studied for static users [5], 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 [6]. For example, in [7], the locations of the UAV are updated according to the users' locations to maximize the long-time network throughput. It is imperative that for UAV-assisted communications, the network performance is impacted by user mobility [8]. Therefore the direction of interest to be sensed, and the time interval between two consecutive UAV placement intervals (trajectory optimization) must be determined based on the user mobility. This issue has not been considered in the prior literature. Moreover, when users' mobility is considered in existing literature, constant mobility is assumed for all users [8] which is not necessarily the case in an ultradense network.

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.

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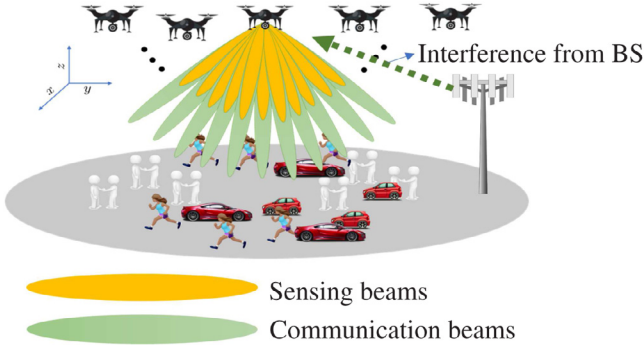
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**Fig. 1.** Example scenario showing multiple UAVs and UEs with varying degrees of mobility.

## 2. System model

We assume a communication network with  $K$  multiple users (UE) and  $M$  multiple UAVs as presented in Fig. 1. Each UAV is assumed to be equipped with multiple  $N_t$  uniform linear array antennas, and a single antenna is employed at each UE. In addition, each UAV is assumed to be equipped with an integrated sensing and communication module allowing for simultaneous sensing and communication. This work aims to optimize the sensing and communication resources subject to the users' mobility level.

### 2.1. Users dynamics

For simplicity, consider a network consisting of users (UE) characterized 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

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

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, a dynamic model is considered at the UEs which comprises a command process vector  $\mathbf{v}_k = [v_x^k, v_y^k, v_z^k]^T$  and a random acceleration vector  $\boldsymbol{\omega}_k = [\omega_x^k, \omega_y^k, \omega_z^k]^T$ , hence, allowing for a total acceleration of  $\boldsymbol{\alpha}_k = \boldsymbol{\omega}_k + \mathbf{v}_k$ .

### 2.2. UAV dynamics, sensing and communication model

Given the framework in Fig. 1, each UAV is expected to sense the positions of the UEs and the environment and update their position based on the UE mobility. We define the state vector of the  $m$ th UAV as  $\mathbf{p}_m^n = [u_x^m, u_y^m, u_z^m]^T$  where the subscripts  $x$ ,  $y$  and  $z$  denote the coordinates of the  $m$ th UAV. Suppose  $\mathcal{S}$  denote the set of ground user indices scheduled for communication by the UAVs, then  $m$ th UAV state vector at the  $n$ th time stamp can be expressed as

$$\mathbf{p}_m^n = \mathbf{p}_m^{n-1} + \boldsymbol{\lambda}_l = \mathbf{p}_m^{n-1} + \begin{bmatrix} \delta \cos(l \Delta \theta) \\ \delta \sin(l \Delta \theta) \\ h_l \end{bmatrix}, \quad (2)$$

where  $\boldsymbol{\lambda}_l$  is the set of actions in the  $x$ ,  $y$ , and  $z$  axis of the UAV comprising of  $l = \{1, \dots, N_\theta\}$  command actions,  $N_\theta$  is the maximum actions space (directions a UAV can move in the  $x$ ,  $y$ , and  $z$  axis),  $\delta$  is the constant distance that a UAV can travel between two consecutive timesteps  $\Delta n$ ,  $\Delta \theta = 2\pi/N_\theta$  represents the unit steering angle of the  $m$ th UAV, and  $h_l$  is the discrete altitude.

A line of sight (LoS) and non-LoS (NLoS) channel model that takes into account the UAV's altitude, elevation angle and probability of the LoS path to the UE is considered in this paper. Consider the  $m$ th UAV at an altitude of  $h_m$  and a distance  $r_{k,m}$  towards the  $k$ th UE, the probability of LoS path can be evaluated as [9]

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

where  $d_{k,m}$  denotes the horizontal distance on a 2D plane from the UE to the projected position of the UAV, the parameters  $\epsilon$  and  $\beta$  are environment-dependent parameters. The path loss to the  $k$  can be expressed as

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

where  $\zeta_{\text{LoS}}$  and  $\zeta_{\text{NLoS}}$  are the losses associated with the LoS and NLoS path respectively. We define  $k$ th UE signal-to-interference plus noise ratio as

$$\gamma_{k,m}^o = \frac{P_{k,m} g_{k,m} L_{k,m}(r_{k,m}, d_{k,m})}{\sum_{j \neq m} P_{k,j} g_{k,j} L_{k,j}(r_{k,j}, d_{k,j}) + P_{k,BS} g_{k,BS} L_{k,BS}(r_{k,BS}, d_{k,BS}) + \sigma^2}. \quad (5)$$

where  $g_{k,m}$  is the channel gain between the  $m$ th UAV and  $k$ th UE,  $P_{k,m}$ ,  $P_{k,j}$  and  $P_{k,BS}$  are the transmit power from the  $m$ th UAV, interfering  $j$ th UAVs and the BS respectively. Given the system description above, the average spectral efficiency at the receiver of the  $k$ th UE from the serving  $m$ th UAV ( $C_{k,m}$ ) is given by

$$C_{k,m} = \mathbb{E}[\log_2(1 + \gamma_{k,m})]. \quad (6)$$

Considering user fairness, the allocated bandwidth to the  $k$ th UE is adjusted at serving UAV according to the quality of the link such that the rate at the  $k$ th UE from the serving  $m$ th UAV is given by  $R_{k,m} = b_{k,m} C_{k,m}$ , where  $b_{k,m}$  is the bandwidth allocated to the  $k$ th UE from the  $m$ th UAV.

### 2.3. Mobility-aware resource allocation and UAV trajectory update time problem formulation

Our objective is to exploit the mobility level of the UEs to allocate the bandwidth resource for joint communication and sensing as shown in Fig. 2. Hence, a mobility-aware resource allocation-constrained optimization problem is formulated as follows

$$\max_{\mathbf{A}, \mathbf{p}_m^n} \sum_{m \in \mathcal{U}} \sum_{k \in \mathcal{S}} a_{k,m} R_{k,m}, \quad (7a)$$

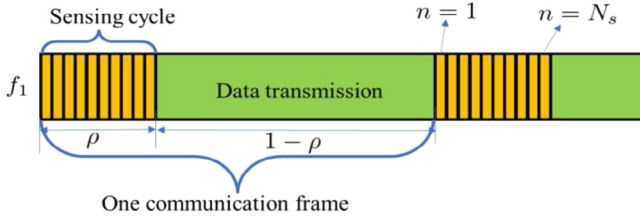


Fig. 2. Frame structure of the conventional ISAC-enabled system.

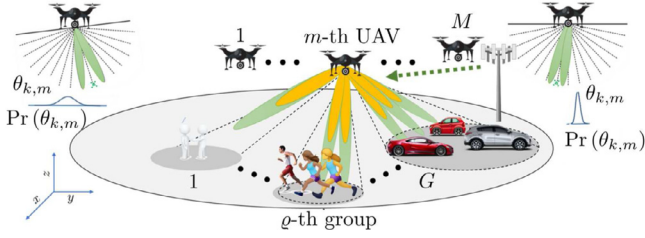


Fig. 3. Example scenario of proposed resource allocation based on users' mobility levels showing multiple UAVs and UE clusters.

$$\text{s.t. } R_{k,m} \geq b_{k,m} C_{k,m}, \quad \forall k \in \mathcal{S}, \forall m \in \mathcal{U}, \quad (7b)$$

$$\sum_k a_{k,m} b_{k,m} \leq B_m, \quad \forall m \in \mathcal{U}, \quad (7c)$$

$$\mathbf{I}^{\min} \leq \mathbf{p}_m^n \leq \mathbf{I}^{\max}, \quad \forall m \in \mathcal{U}, \quad (7d)$$

$$\mathbf{a}_{k,m} | T_{k,m}(x, y) \in \{0, 1\}, \quad (7e)$$

$$\sum_m \mathbf{a}_{k,m} \leq 1, \quad \forall (k, m) \in \mathcal{U} \times \mathcal{S}, \quad (7f)$$

where  $\mathbf{A} \in \mathbb{R}^{K \times M} = (a_{k,m})$  denote the UAV-UE association matrix, the vectors  $\mathbf{I}^{\min}$  and  $\mathbf{I}^{\max}$  respectively define the minimum and maximum boundaries in the  $x$ ,  $y$  and  $z$  axis for the UAVs. The minimum rate requirement is achieved by the constraint in (7b) to ensure user fairness, the available bandwidth at each UAV is upper bounded by the maximum bandwidth constraint  $B_m$  in (7c). (7d) ensures that the communication is limited to the service area while subjecting the trajectory optimization of the UAV within the communication boundaries. Finally, the mobility-aware UAV-UE association matrix is optimized based on the constraint in (7e) and (7f) ensuring an association only between a single UAV and UE where  $T_{k,m}(x, y)$  is the transmission probability and will be defined in the subsequent section.

### 3. Proposed user mobility level characterization and UAV-UEs association

To address the resource allocation problem formulated above, we begin by characterizing the user's mobility level. Using the information from the user's dynamics in (1), the 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

$$T_{k,m}(x, y) = \frac{1}{C} \exp(-|x_{k,m} - y_{k,m}|^2 / \sigma_{k,m}^2), \quad (8)$$

where  $C$  is the normalization constant,  $x_{k,m}$ ,  $y_{k,m}$  denote the relative position between  $k$ th UE and  $m$ th UAV in the  $x$  and  $y$  axis,  $\sigma_{k,m}$  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 (2). That is, the mobility level  $\sigma_{k,m}$  of the  $k$ th UE can be obtained by obtaining the speed of the UE from any two consecutive sensed information in (1) and (2),

Given the beam split algorithm in our previous work [10], the beam from the  $m$ th UAV to the direction of the  $k$ th UE can be expressed as

$$\mathbf{f}_{k,m} = \sqrt{1 - \rho} \mathbf{v}_{k,m} + \sqrt{\rho} e^{j\psi} \mathbf{w}_{m,n}, \quad (9)$$

where  $\mathbf{v}_{k,m}$  is the analog beamformer for communicating with the  $k$ th UE,  $\rho$  is the beam split factor and  $\psi$  is the phase adjustment parameter and  $\mathbf{w}_{m,n}$  is the sensing beamformer in the  $n$ th direction of interest.

The beam split ratio  $\rho$  is optimized to maximize the sum rate at each time step based on the user's mobility level and the transition probability.

Given the optimized beamformer  $\mathbf{f}_{k,m}$ , the average sum rate can be evaluated as

$$C_{k,m,\rho} = \sum_{\rho=1}^G \sum_{m=1}^M \sum_{k=1}^K a_{k,m} b_{k,m} \mathbb{E}[\log_2(1 + |\mathbf{f}_{k,m}|^2 \gamma_{k,m}^{\rho})], \quad (10)$$

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.

Conventionally, the  $K$ -means (KM) algorithm can be implemented for UAV-UE association, due to the limited space, we refer our readers to [11]. In [12], the Gaussian mixture model (GMM) algorithm is highlighted for users' classification. In this paper, we propose a modified Gaussian mixture model algorithm with  $K$ -mean initialization. The algorithm is presented in Algorithm 1.

### 4. 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 Table 1. 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). For ease of notation in the figures, the proposed algorithm is presented as “ISAC-UAV-GM-K”, the UAV-UE association based on GMM algorithm is defined as “UAV-UE association with GMM” while the UAV-UE association with  $k$ -means algorithm is presented as “UAV-UE association with KM”.

In Fig. 4, the average sum rate versus the number of UAVs is presented. The results show an upward trend as the

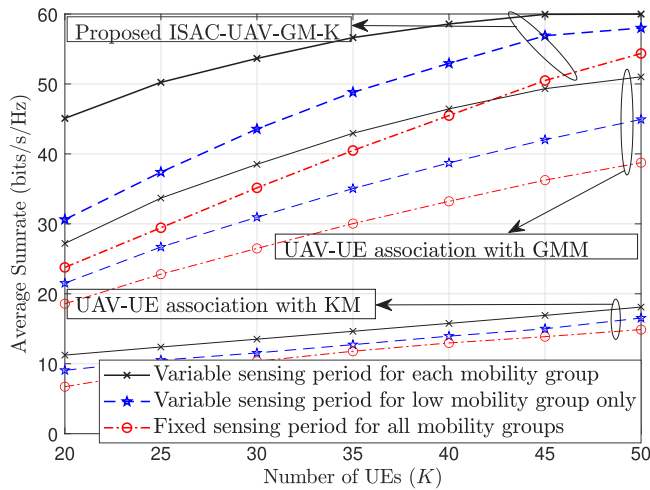
**Algorithm 1:** Proposed ISAC-UAV-GM-K Algorithm

**Input:**  $\mu = M$ ,  $\mathbf{x} = [\mathbf{x}_k[n] - \mathbf{x}_k[n - 1]]^T$ ,  $K$ ,  $\mathbf{x}_k[n]$ ,  $\mathbf{u}_m^n$   
**Output:**  $\mathbf{A}$ ,  $\rho$ ,  $\mathbf{v}_{k,m}$ ,  $\mathbf{w}_{k,m}$ ,  $\mathbf{f}_{k,m}$

- 1 Initialize users mobility levels  $\sigma_{k,m}$  from a mobility level set;
- 2 Initialize  $\Sigma$  and mixing coefficient  $\pi$  with random weights;
- 3 **for**  $Timeslot = 1, \dots, T$  **do**
- 4     Compute the SINR given by (5)  $\forall m, k$ ;
- 5     Evaluate mean  $\mu$  for UAV initial positions based on K-mean Algorithm [10];
- 6     Evaluate the log-likelihood  $L(\mathbf{x}|\mu, \Sigma) = \ln \frac{1}{2\pi^{D/2}} \frac{1}{|\Sigma|^{1/2}} \exp \{-\frac{1}{2}(\mathbf{x} - \mu)^T \Sigma^{-1}(\mathbf{x} - \mu)\}$ ;
- 7     Evaluate the responsibility function given by (7a)–(7f) with current parameters;
- 8     Obtain new  $\mu$ ,  $\Sigma$ , and mixing coefficient  $\pi$  using newly obtained responsibilities;
- 9     Compute the  $L$  and repeat steps 7 and 8 until convergence ( $\epsilon$ );
- 10 **end**

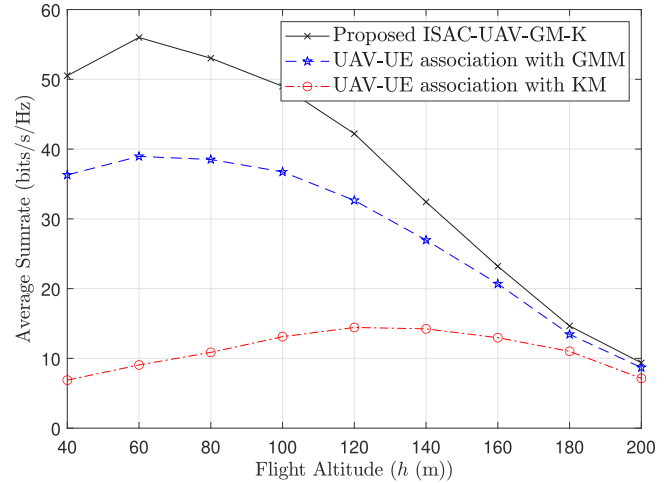
**Table 1**  
Summary of simulation parameters.

Parameters	Values
Frame duration $T$	20 ms
Sampling time $t_p$	0.2 ms
Number of UEs per group $K_g$	30
Number of groups $G$	10
SNR $\gamma$	-10 dB
Transmit power	$P_{k,m}, P_{k,BS} = 30$ dBm
Convergence criteria $\epsilon$	$10^{-6}$



**Fig. 4.** Average sum rate versus number of users for various UAV-UE association algorithm.

number of users increases. However, the average sum rate gradually decreases as the number of UE increases due to the limited bandwidth in (7c). The constraint ensures that the rate continues to increase but cannot exceed the total bandwidth, hence, the average sum rate gradually reduces as it approaches the maximum capacity. Furthermore, the results



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

show that compared with a fixed sensing interval and varying sensing interval for low mobility only, the proposed ISAC-UAV GM-K with variable sensing  $\rho$  for each mobility group achieves much better performance when compared with the conventional UAV-UE association with GMM and UAV-UE association with KM.

Fig. 5, shows the average sum rate against UAV altitude. The results show an increase in the initial flight altitude. However, as the flight altitude increases, the average sum rate decreases due to interference and path loss between the UAV and UE. Furthermore, as the service area increases, the path loss between the UAVs and the user could also impact the system’s achievable sum rate. Overall, the proposed method can reduce the sensing overhead and thereby, improve the resource allocation for joint communication and sensing.

**5. 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 sensing and communication resource allocation based on the group mobility level.

**Declaration of competing interest**

The authors declare that there is no conflict of interest in this paper.

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