Sensing Fairness Based Energy Efficiency Optimization for UAV Enabled Integrated Sensing and Communication

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***Abstract*—Integrated sensing and communication (ISAC) is developing rapidly due to the advantages of bandwidth saving, hardware cost reduction and energy saving. This paper proposes a unmanned aerial vehicle (UAV) enabled ISAC (UAV-ISAC) system, where the UAV will sense ground users and forward sensed information to base station (BS). Radar mutual information (MI) is introduced to measure the UAV sensing performance. On the basis of sensing fairness for each user, a multi-objective resource optimization problem of maximizing both energy efficiency (EE) and minimum radar MI is studied by jointly optimizing user scheduling, transmit power and UAV trajectory. To solve the non-convex optimization problem, we decompose it into three sub-problems: user scheduling optimization, transmit power optimization, and UAV trajectory optimization. Each subproblem can be solved by successive convex approximation (SCA), fractional programming and relaxation technique. By iteratively optimizing the three sub-problems, we can obtain the suboptimal solution to original optimization problem. Simulation results show that the proposed optimization scheme can maximize the EE of UAV while ensuring sensing fairness for all users.**

***Index Terms*—UAV, ISAC, resource optimization, radar mutual information, fairness, energy efficiency.**

I. INTRODUCTION

The future 5G network aims to provide users with richer business experiences, which will not only support communication services with high bandwidth, but also provide sensing services such as target detection, positioning, recognition etc. However, the introduction of sensing functions has led to a shortage of spectrum resources [1]. Currently, unmanned Aerial Vehicle (UAV), owing to its high mobility, low cost and easy deployment, are widely used in the 5G network to assist ground communications. To achieve sensing and communication functions, the traditional UAVs load with radar and communication devices independently, which will waste spectrum resources and increase energy consumption. Integrated sensing and communication (ISAC) technology is a good solution to improve spectrum utilization and reduce hardware energy consumption by integrating communication and sensing functions in one device with the same frequency band [2]. In [3], Wang *et al.* proposed a joint optimization problem of UAV localization, user association and transmit power to maximize the total utility of UAV-ISAC network under the localization accuracy constraints of UAVs. In [4], Meng *et al.* jointly optimized UAV trajectory, user association, target sensing selection, and transmit beamforming, so that the rate of UAV-ISAC system could be maximized while meeting the requirements of sensing frequency and beam pattern gain for a given target. In [5], Chen *et al.* proposed a cooperative UAV-ISAC network, where the UAVs could simultaneously conduct cooperative radar detection and data-fusion communication. The cooperative sensing performance was improved by optimizing the upper-bound average cooperative sensing area. However, the study in [3] is devoted to static UAV, which ignores the high mobility of the UAV, while the studies in [4] and [5] only consider the communication rate and sensing performance of the ISAC system and ignores the energy efficiency (EE) of the UAV.

While the UAVs bring many performance advantages to ISAC, there also exists many challenges such as energy shortages and power limitations. Compared with the traditional communication systems, the UAV-ISAC system will consume more energy for both sensing and communication, which will increase the power consumption of energy-limited UAV. Therefore, EE optimization is very important for the UAV-ISAC system to achieve tradeoff between energy consumption and ISAC performance. In this paper, by deploying the UAV as a dual-function (sensing and communication) aerial platform, we propose a UAV-ISAC system to sense ground users and forward sensed information to a central base station (BS). Considering both UAV energy consumption (ISAC power and propulsive power) and sensing fairness, the EE of the UAV-ISAC is maximized while the sensing fairness of each user is guaranteed. The main contributions of this paper are summarized as follows:

- We propose a UAV-ISAC system, where the UAV simultaneously senses the ground users and forwards the sensed information to the BS. We introduce radar mutual information (MI) from an information-theoretic perspective to measure radar sensing performance of UAV-ISAC system.
- To decrease UAV-ISAC energy consumption and ensure sensing fairness, we propose a multi-objective optimization problem to maximize both the EE of the UAV-ISAC system and minimum user radar MI by jointly optimizing

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user scheduling, transmit power and UAV trajectory. The original non-convex optimization problem can be decomposed into three subproblems, user scheduling optimization, transmit power optimization, and UAV trajectory optimization, which can be solved by successive convex approximation (SCA), fractional programming and relaxation technique. Finally, the optimal solution to the original problem can be obtained by optimizing the three subproblems iteratively.

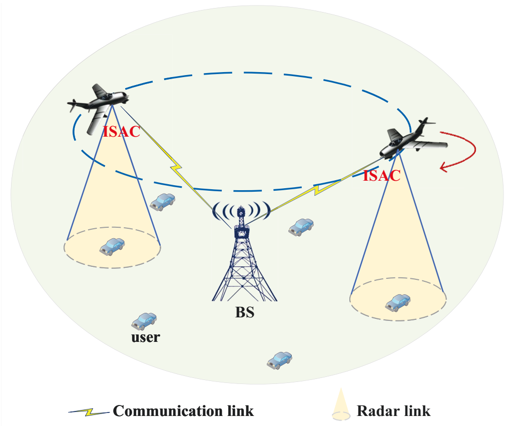

Fig. 1. UAV-ISAC system model.

II. System Model

A. System Model

In Fig. 1, we consider a UAV-ISAC system consisting of one UAV, K users and one BS. During the UAV flight, the UAV-ISAC system simultaneously senses the ground users and forwards the sensed information to the BS. The coordinates of user $k \in \mathcal{K} = \{1, 2, ...K\}$ are expressed as $w_k = [x_k, y_k]^T$ and the coordinates of BS is expressed as $l = [x_l, y_l]^T$. We assume that flight time T and flight altitude H of the UAV are constant. We divide T into S equal time slots, each of which is denoted as $\delta_t = \frac{T}{S}$. Each time slot is small enough to treat the UAV motion parameters as constants. In Fig. 2, we divide each time slot into two sub-time slots. In the first sub-time slot, the UAV senses the user, and in the second sub-time slot, it sends the sensed information to the BS. The position and velocity of the UAV in time slot $s \in \mathcal{S} = \{1, 2, ...S\}$ can be expressed as $u\left(s\right) = \left(x(s), y(s)\right)^T$ and $v\left(s\right)$, respectively. The kinematics formula of the UAV can be expressed as

$$u\left(s+1\right) = u\left(s\right) + v(s)\delta_t + \frac{1}{2}\omega(s)\delta_t^2, \forall s \tag{1}$$

$$v\left(s+1\right) = v\left(s\right) + \omega(s)\delta_t, \forall s \tag{2}$$

where $\omega(s)$ is the acceleration of the UAV.

We assume that each UAV flies periodically, i.e. $u\left(1\right) = u\left(S\right)$ and $v\left(1\right) = v\left(S\right)$. The motion parameters of the UAV are constrained as $v_{\min} \le \left\|v\left(s\right)\right\| \le v_{\max}, \forall s$ and $\left\|\omega\left(s\right)\right\| \le \omega_{\max}, \forall s$, where $v_{\max}$ and $\omega_{\max}$ are the maximum velocity and acceleration, respectively, and $v_{\min}$ is the minimum velocity. The channel power gain of the communication link from UAV to BS at time slot s can be expressed as

$$h^c(s) = \frac{G_t G_c \lambda^2}{(4\pi)^2 d^2(s)} = \frac{\rho_{com}}{d^2(s)} \tag{3}$$

where G_t and G_c are the antenna gains of UAV transmitter and user receiver, respectively, $d(s)$ is the distance from UAV to BS, λ is wavelength, and $\rho_{\text{com}} = \frac{G_t G_c \lambda^2}{(4\pi)^2}$. The channel power gain of the radar detection link from UAV to user k at time slot s can be expressed as

$$h_k^r(s) = \frac{G_t G_r \lambda^2 \sigma}{(4\pi)^3 d_k^4(s)} = \frac{\rho_{rad}}{d_k^4(s)} \tag{4}$$

where G_r is the antenna gain of UAV radar receiver, σ denotes target radar cross-section (RCS), $d_k(s)$ is the distance from UAV to user k, and $\rho_{rad} = \frac{G_t G_r \lambda^2 \sigma}{(4\pi)^3}$.

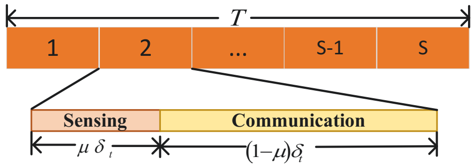

Fig. 2. Time slot division.

We introduce binary variables $a_k(s)$ to indicate user scheduling of ISAC tasks. When the UAV performs an ISAC task for user k at time slot s, $a_k(s) = 1$, otherwise, $a_k(s) = 0$. The UAV only schedules one user per time slot, which yields the constraints $a_k(s) \in \{0, 1\}, \forall s, k$ and $\sum_{k=1}^{K} a_k(s) \le 1, \forall s$.

The signal-to-noise ratio (SNR) of the communication link can be expressed as $\Gamma^c(s) = \frac{p(s)h^c(s)}{N_0}$, where N_0 is the power of additive white Gaussian noise (AWGN), and $p(s)$ is the transmit power of UAV. Similarly, the SNR of the radar link can be expressed as $\Gamma_k^r(s) = \frac{p(s)h_k^r(s)}{N_0}$. To ensure the sensing accuracy, the radar SNR in each time slot needs to satisfy

$$\Gamma_k^r(s) \ge \Gamma_{th}^r, \ \forall s \tag{5}$$

where Γ_{th}^r is the SNR lower bound for reliable radar detection. The radar MI characterizes the amount of information between the detected target and the radar signal. The larger the radar MI, the more target information the received signal contains [6]-[7]. The radar MI for sensing user k in time slot s is expressed as

$$R_k^{rad}(s) = a_k(s)\mu\log_2(1 + \Gamma_k^r(s)) \tag{6}$$

where μ is the allocation factor of time slot. The total radar MI for user k can be expressed as

$$R_k^{rad} = \sum_{s=1}^{S} R_k^{rad}(s), \forall k \tag{7}$$

The communication rate of UAV to BS at time slot s can be expressed as

$$R^{com}(s) = (1-\mu)\log_2(1 + \Gamma^c(s)) \tag{8}$$

The total communication capacity sent by the UAV can be expressed as

$$R^{com} = \sum_{s=1}^{S} (1-\mu)\log_2(1+\Gamma^c(s)) \tag{9}$$

To ensure that the UAV can send all the sensed information to the BS, the communication capacity needs to be more than the radar MI in each time slot. It can be expressed as

$$R^{com}(s) \ge R_k^{rad}(s), \forall k, s \tag{10}$$

The propulsive power of a fixed-wing UAV is defined as

$$\hat{p}(s) = a\|v(s)\|^3 + \frac{b}{\|v(s)\|}\left(1+\frac{\|\omega(s)\|^2}{g^2}\right) \tag{11}$$

where g is the gravitational acceleration, a and b are the constant parameters related to the UAV wing area, UAV weight and air density. The total energy consumption of the UAV can be expressed as

$$E_{total} = \sum_{s=1}^{S} (p(s)+\hat{p}(s)) \tag{12}$$

B. Problem Formulation

To maximize EE of UAV-ISAC system while guaranteeing sensing fairness, we jointly optimize user scheduling **A**=$\{a_k(s), \forall s, k\}$, transmit power **P**=$\{p(s), \forall s\}$, and UAV trajectory **U**=$\{u(s), \forall s\}$. The multi-objective optimization problem can be formulated as follows

$$\begin{aligned}
&\max_{\mathbf{A,P,U}} \frac{R^{com} + \sum\limits_{k=1}^{K} R_k^{rad}}{E_{total}} && \text{(13a)}\\
&\max_{\mathbf{A,P,U}} \min R_k^{rad}, \forall k && \text{(13b)}\\
\text{s.t.}\quad & a_k(s) \in \{0,1\}, \forall s, k && \text{(13c)}\\
&\sum_{k=1}^{K} a_k(s) \le 1, \forall s && \text{(13d)}\\
&R^{com}(s) \ge R_k^{rad}(s), \forall k, s && \text{(13e)}\\
&\Gamma_k^r(s) \ge \Gamma_{th}^r, \forall s && \text{(13f)}\\
&0 \le \frac{1}{S}\sum_{s=1}^{S} p(s) \le p_{\max}, \forall s && \text{(13g)}\\
&u(s+1) = u(s) + v(s)\delta_t + \frac{1}{2}\omega(s)\delta_t^2, \forall s && \text{(13h)}\\
&v(s+1) = v(s) + \omega(s)\delta_t, \forall s && \text{(13i)}\\
&u(1) = u(S),\ v(1) = v(S) && \text{(13j)}\\
&v_{\min} \le \|v(s)\| \le v_{\max}, \forall s && \text{(13k)}\\
&\|\omega(s)\| \le \omega_{\max}, \forall s && \text{(13l)}
\end{aligned}$$

where $p_{\max}$ is the maximum transmit power of UAV. To achieve fair radar MI, we set the variable $\zeta = \min R_k^{rad}$ [8]-[9], and $R^{com} + K\zeta$ is a lower bound of $R^{com} + \sum_{k=1}^{K} R_k^{rad}$. Thus, the optimization problem can be rewritten as

$$\begin{aligned}
&\max_{\mathbf{A,P,U}} \frac{R^{com} + K\zeta}{E_{total}} && \text{(14a)}\\
\text{s.t.}\quad & R_k^{rad} \ge \zeta, \forall k && \text{(14b)}\\
&(13c) - (13l) && \text{(14c)}
\end{aligned}$$

We can see that problem (14) is hard to solve directly due to the binary integer constraint for (13c) and the non-convex constraints for (13e) , (14b).

III. PROPOSED SOLUTION

In order to solve problem (14), we decompose the original optimization problem into three subproblems, user scheduling optimization, transmit power optimization, and UAV trajectory optimization. Then, we acquire the solution to the original problem by solving the three subproblems iteratively until the objective function is convergent.

A. User Scheduling Optimization

For any given transmit power **P** and trajectory **U**, the user scheduling optimization subproblem can be described as

$$\begin{aligned}
&\max_{\mathbf{A}} \frac{R^{com} + K\zeta}{E_{total}} && \text{(15a)}\\
\text{s.t.}\quad & (13c) - (13f), (14b) && \text{(15b)}
\end{aligned}$$

which is a fractional programming problem. We can transform its objective function into a linear form[10]. Let the variables $\eta = \frac{R^{com}+K\zeta}{E_{total}}$, we transform the objective function into $R^{com} + K\zeta - \eta E_{total}$.

Since (13c) is a binary constraint, we convert $a_k(s)$ to a continuous variable $0 \le a_k(s) \le 1$. Thus, the scheduling subproblem can be expressed as

$$\begin{aligned}
&\max_{\mathbf{A}} (R^{com} + K\zeta - \eta E_{total}) && \text{(16a)}\\
\text{s.t.}\quad & 0 \le a_k(s) \le 1 && \text{(16b)}\\
&(13d) - (13f), (14b) && \text{(16c)}
\end{aligned}$$

Since problem (16) is a standard linear problem (LP), it can be directly solved by the MATLAB CVX.

B. Transmit Power Optimization

For a known scheduling **A** and trajectory **U**, the transmit power optimization subproblem can be described as

$$\begin{aligned}
&\max_{\mathbf{P}} (R^{com} + K\zeta - \eta E_{total}) && \text{(17a)}\\
\text{s.t.}\quad & (13e), (13f), (13g), (14b) && \text{(17b)}
\end{aligned}$$

where (13e) is a non-convex constraint. We can easily obtain an upper bound for $R_k^{rad}(s)$ as

$$R_k^{rad}(s) = a_k(s)\mu\log_2\left(1+\frac{p(s)h_k^r(s)}{N_0}\right) \le \tilde{R}_k^{rad}(s) = a_k(s)\mu\left(\log_2\left(1+\frac{p^i(s)h_k^r(s)}{N_0}\right) + A(s)\left(p(s)-p^i(s)\right)\right) \tag{18}$$

where $A(s) = \frac{h_k^r(s)\log_2 e}{N_0 + p^i(s)h_k^r(s)}$ and $p^i(s)$ is the value of $p(s)$ in the i-th iteration. Thus, the transmit power optimization subproblem can be written as

$$\max_{\mathbf{P}}(R^{com} + K\zeta - \eta E_{total}) \tag{19a}$$

$$\text{s.t.} \quad R^{com}(s) \geq \tilde{R}_k^{rad}(s), \forall k, s \tag{19b}$$

$$(13f), (13g), (14b) \tag{19c}$$

which is a convex optimization problem that can be solved using CVX's MOSEK solver.

C. UAV Trajectory Optimization

For fixed scheduling $\mathbf{A}$ and transmit power $\mathbf{P}$, the UAV trajectory optimization subproblem can be described as

$$\max_{\mathbf{U}}(R^{com} + K\zeta - \eta E_{total}) \tag{20a}$$

$$\text{s.t.} \quad (13e), (13f), (13h) - (13l), (14b) \tag{20b}$$

where the objective function and the constrains (13e), (13k), (14b) are all non-convex. Thus, we can use the SCA and relaxation technique to solve (20). The lower bound of $R^{com}(s)$ can be given by

$$\begin{aligned} & R^{com}(s) = (1-\mu)\log_2\left(1 + \tfrac{\rho_{com}p(s)/N_0}{H^2 + \|u(s)-l\|^2}\right) \geq \breve{R}^{com}(s) \\ & = (1-\mu)\left(C(s) - B(s)\left(\|u(s)-l\|^2 - \left\|u^i(s)-l\right\|^2\right)\right) \end{aligned} \tag{21}$$

where $B(s)$ and $C(s)$ can be expressed as

$$B(s) = \frac{\rho_{com}p(s)/N_0/\ln 2/\left(H^2 + \left\|u^i(s)-l\right\|^2\right)}{\left(H^2 + \|u^i(s)-l\|^2 + \frac{\rho_{com}p(s)}{N_0}\right)} \tag{22}$$

$$C(s) = \log_2\left(1 + \frac{\rho_{com}p(s)/N_0}{H^2 + \left\|u^i(s)-l\right\|^2}\right) \tag{23}$$

where $u^i(s)$ is the UAV trajectory in the i-th iteration. Thus, the lower bound for the total communication capacity can be expressed as

$$\breve{R}^{com} = \sum_{s=1}^{S} \breve{R}^{com}(s) \tag{24}$$

Similarly, we can obtain

$$\begin{aligned} & \log_2\left(1 + \tfrac{\rho_{rad}p(s)/N_0}{\left(H^2+\|u(s)-w_k\|^2\right)^2}\right) \geq \\ & E(s) - D(s)\left(\|u(s)-w_k\|^2 - \left\|u^i(s)-w_k\right\|^2\right) \end{aligned} \tag{25}$$

where $D(s)$ and $E(s)$ can be expressed as

$$D(s) = \frac{2\rho_{rad}p(s)/N_0/\ln 2/\left(H^2 + \left\|u^i(s)-w_k\right\|^2\right)}{\left(\left(H^2 + \|u^i(s)-w_k\|^2\right)^2 + \frac{\rho_{rad}p(s)}{N_0}\right)} \tag{26}$$

$$E(s) = \log_2\left(1 + \frac{\rho_{rad}p(s)/N_0}{\left(H^2 + \left\|u^i(s)-w_k\right\|^2\right)^2}\right) \tag{27}$$

Thus, the lower bound of $R_k^{rad}(s)$ can be expressed as

$$\begin{aligned} & R_k^{rad}(s) \geq \breve{R}_k^{rad}(s) = a(s)\mu \\ & \left(E(s) - D(s)\left(\|u(s)-w_k\|^2 - \left\|u^i(s)-w_k\right\|^2\right)\right) \end{aligned} \tag{28}$$

By introducing the auxiliary variable $\chi = \chi_k(s), \forall k, s$, We can get the upper bound of $R_k^{rad}(s)$ as

$$\begin{aligned} & R_k^{rad}(s) \leq \overset{\frown}{R}_k^{rad}(s) = \\ & a_k(s)\mu(s)\log_2\left(1 + \tfrac{\rho_{rad}p(s)/N_0}{(H^2+\chi_k(s))^2}\right) \end{aligned} \tag{29}$$

$$\chi_k(s) \leq \|u(s)-w_k\|^2, \forall s, k \tag{30}$$

To deal with the non-convex denominator of objective function and constraint (13k), we introduce a slack variable β. Then E_{total} can be rewritten as

$$\tilde{E}_{total} = \sum_{s=1}^{S}\left(a\|v(s)\|^3 + \frac{b}{\|\beta\|}\left(1 + \frac{\|\omega(s)\|^2}{g^2}\right) + p(s)\right) \tag{31}$$

where β needs to be no more than $v(s)$. Then, we can get

$$\|v(s)\|^2 \geq \beta^2 \tag{32}$$

$$\beta \geq v_{\min} \tag{33}$$

According to the Taylor formula, we can get the lower bound of $v(s)$ as

$$\begin{aligned} & \|v(s)\|^2 \geq \left\|\breve{v}(s)\right\|^2 = \\ & \left\|v^i(s)\right\|^2 + 2v^i(s)^T\left(v(s) - v^i(s)\right) \end{aligned} \tag{34}$$

where $v^i(s)$ is the value of $v(s)$ in the i-th iteration.

Thus, the trajectory optimization subproblem can be rewritten as

$$\max_{\mathbf{U}}(\breve{R}^{com} + K\zeta - \eta\tilde{E}_{total}) \tag{35a}$$

$$\text{s.t.} \quad \sum_{s=1}^{S}\breve{R}_k^{rad}(s) \geq \zeta, \forall k \tag{35b}$$

$$\breve{R}^{com}(s) \geq \overset{\frown}{R}_k^{rad}(s), \forall k, s \tag{35c}$$

$$\left\|\breve{v}(s)\right\|^2 \geq \beta^2, \forall s \tag{35d}$$

$$v(s) \leq v_{\max}, \forall s \tag{35e}$$

$$(13f), (13h) - (13j), (35). \tag{35f}$$

where (35a)-(35f) are all convex. We can use the CVX's Mosek solver to solve this subproblem.

The iterative optimization scheme is proposed in Algorithm 1, which can achieve the suboptimal solution to the original optimization problem by iteratively optimizing the three subproblems until the objective function is convergent.

IV. SIMULATION RESULTS

We assume 9 users are randomly distributed in the square area of 1000m × 1000m. The flight height of UAV is 100m, the maximum transmit power of UAV is 1W, and the maximum and minimum flight speeds of UAV are 60m/s and 3m/s,

Algorithm 1 Iterative optimization for problem (13).

```
initialize $i$=0, $\mathbf{U}^{[i]}$ and $\mathbf{P}^{[i]}$;
repeat
    solve the scheduling optimization subproblem (16) for the given $\mathbf{U}^{[i]}$ and $\mathbf{P}^{[i]}$, and obtain the suboptimal solution $\mathbf{A}^{[i+1]}$;
    solve the power optimization subproblem (19) for the given $\mathbf{A}^{[i+1]}$ and $\mathbf{U}^{[i]}$, and obtain the suboptimal solution $\mathbf{P}^{[i+1]}$;
    solve the trajectory optimization subproblem (35) for the given $\mathbf{A}^{[i+1]}$ and $\mathbf{P}^{[i+1]}$, and obtain the suboptimal solution $\mathbf{U}^{[i+1]}$;
    $i = i + 1$;
until the objective value converges within a specified threshold $\varepsilon$.
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respectively. The total flight time T is 45s, the number of time slots S is 90, and the sub-time slot weight μ is 0.5. The target RCS σ is 1 m^2, and the noise power N_0 is -110dBmW. The UAV transmitter antenna gain G_t, UAV radar receiver antenna gain G_r and BS receiver antenna gain G_c are 20dBi, 30dBi and 0dBi, respectively. The propulsion power coefficients a, b, g are 0.001, 2250, 9.8, respectively. The radar SNR threshold Γ_{th}^{r} is 20dB, and the algorithm convergence threshold ε is 10^{-4}.

In Fig. 3, we compare the UAV trajectory of our scheme (ISAC-Max EE with sensing fairness) with that of traditional ISAC-Max EE without fairness scheme. We can see that compared with ISAC-Max EE without fairness scheme, the UAV trajectory in our scheme will be as close as possible to each user in order to satisfy sensing fairness. In Fig. 4, we compare the radar MI of each user between our scheme and the max EE scheme. We can see that our scheme can achieve better radar MI fairness for each user, while the max EE scheme has different radar MI for each user, where the UAV even does not provide sensing service for user 1 and user 4. In Fig. 5, we compare the EE between our scheme, the max EE scheme, and the max EE scheme with initial trajectory under different $p_{\max}$. We can see that although our scheme sacrifices some EE for achieving sensing fairness, the EE of our scheme with trajectory optimization is also better than that of the max EE scheme with initial trajectory.

V. CONCLUSIONS

In this paper, we propose a UAV-ISAC system to simultaneously sense the ground users and forward the sensed information to the BS. To decrease energy consumption and ensure sensing fairness, we propose a multi-objective optimization problem to maximize both EE of UAV-ISAC and minimum radar MI by jointly optimizing user scheduling, transmit power and UAV trajectory. The simulation results show that our scheme is able to maximize the EE of UAV-ISAC system while guaranteeing sensing fairness.

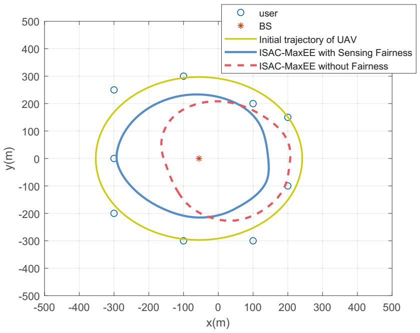

Fig. 3. UAV trajectory.

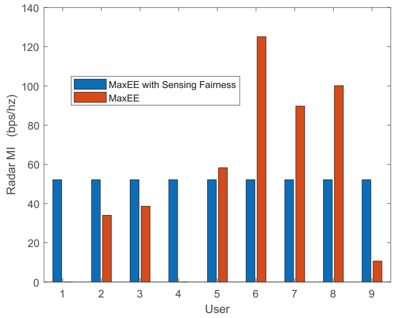

Fig. 4. Radar MI of each user

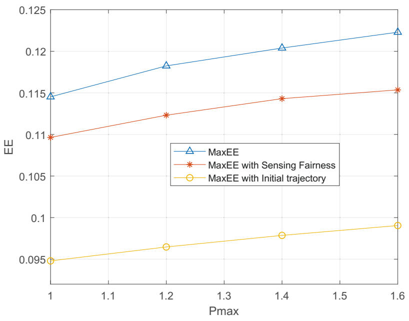

Fig. 5. EE comparison between three schemes

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