Beaconing Design and Trajectory Optimization for UAV-Empowered Adaptable Integrated Sensing and Communication

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Abstract—Unmanned aerial vehicle (UAV) has high flexibility and controllable mobility, therefore it is considered as a promising enabler for future integrated sensing and communication (ISAC). In this paper, we propose a novel adaptable ISAC (AISAC) mechanism in the UAV-empowered system, where the UAV performs sensing on demand during communication and the sensing duration is flexibly configured according to the application requirements rather than keeping the same with the communication duration. Our designed mechanism avoids the excessive sensing and waste of radio resources, therefore improving the resource utilization and system performance. In the UAV-empowered AISAC system, we aim at maximizing the average system throughput by optimizing the communication and sensing beamforming as well as the UAV trajectory while guaranteeing the quality-of-service requirements of communication and sensing. To efficiently solve the considered non-convex optimization problem, we propose an efficient alternating optimization algorithm to alternately optimize the communication and sensing beamforming as well as the UAV trajectory to obtain a suboptimal solution. Numerical results validate the superiority of the proposed adaptable mechanism and the effectiveness of the designed algorithm.

Index Terms—Unmanned aerial vehicle (UAV), integrated sensing and communication (ISAC), adaptable ISAC (AISAC), sensing duration, beamforming, trajectory optimization.

I. INTRODUCTION

In recent years, there have been growing concurrent communication and sensing demands on emerging platforms such as autonomous-driving, unmanned aerial vehicles (UAVs), and remote healthcare, which leads to a new paradigm referred to as integrated sensing and communication (ISAC) [1], [2], [3]. By sharing the same spectrum resources and wireless infrastructures between sensing and communication systems, ISAC can provide a number of advantages over the traditional fully separated stand-alone systems, such as significantly reduced cost, and enhanced spectrum efficiency, energy efficiency, and hardware utilization efficiency.

Beamforming plays an important role in improving the system performance of ISAC. Recently, numerous beamforming design methods have been proposed to provide high-quality ISAC services in various ISAC systems [4], [5], [6]. For instance, in the ISAC system where sensing works with the downlink (DL) communication simultaneously [4], a transmit beamforming scheme was proposed to maximize the sensing performance while guaranteeing the signal-to-interference-plus-noise ratio (SINR) requirement of each communication user. In [5], effective transmit beamforming schemes were developed for the separated sensing and communication antenna deployment as well as the shared antenna deployment in the ISAC system. By carefully designing the transmit beamforming for different antenna deployments, the ideal sensing beampattern can be approached under the power budget and communication SINR constraints. Receiver technology also affects the transmit beamforming design. In [6], the authors considered two types of communication receivers with and without sensing interference cancellation capabilities, and designed the optimal beamforming for the two types of receivers separately. In addition, to further explore the potential of ISAC, some works investigated the emerging technologies and approaches to enhance the overall system performance of ISAC, such as reconfigurable intelligent surface-assisted ISAC [7], [8], [9] and artificial intelligence-enabled ISAC [10], [11].

However, the related prior works on ISAC mainly focus on terrestrial networks, which have many inherent limitations, such as signal blockage caused by the surrounding obstacles and scatters on the ground, imperfect coverage due to the limited available infrastructures, and vulnerability to natural disasters or artificial infrastructure damages, resulting in serious performance degradation or even unavailability of ISAC service. Fortunately, UAV has been envisioned as a cost-effective aerial platform to overcome the above limitations and enable ISAC on demand since it has high mobility, flexibility and controllability and can provide the strong air-ground line-of-sight (LoS) channels [12], [13], [14], [15], [16].
In the UAV-empowered ISAC system, in order to fully exploit the design degrees of freedom for improving the system performance, we also need to carefully investigate the UAV location and/or trajectory optimization in addition to designing resource allocation scheme and beamforming. How to jointly design the resource allocation scheme, beamforming, and UAV location and/or trajectory for unleashing the maximum potential of the UAV-empowered ISAC system is an extremely appealing yet challenging problem. At present, the research on the UAV-empowered ISAC system is still in its infancy, and only a few works focused on solving the above joint design problem. In [17], the UAV trajectory and beamforming were jointly designed to improve the performance of the UAV-empowered ISAC system. To further enhance the communication and sensing coverage and increase the integration gain of communication and sensing, a multi-UAV cooperative ISAC system was proposed in [18], in which the user association, UAV location, and power allocation were jointly optimized to maximize the total network utility while guaranteeing the sensing accuracy.

In the above works on UAV-empowered ISAC systems, sensing and communication always work simultaneously and have the same duration. In such a configuration, sensing is performed with fixed time and the sensing duration remains unchanged, which ignores the fact that different sensing applications usually have different requirements for the sensing duration. The sensing duration mainly consists of two basic components, namely, the sensing dwell duration and sensing interval [19], where the sensing dwell duration is the time over which a position is illuminated and the sensing interval is the time between two adjacent sensing. The sensing dwell duration and sensing interval are typically set according to the sensing application type (e.g., scanning, detection, or tracking) and the desired sensing quality (e.g., the probability of false alarms or sensing accuracy). In the modern sensing/radar systems, multi-pulse accumulation technology is widely used for improving the signal-to-noise ratio (SNR) of the target reflected echo [19]. The length of the dwell duration has a direct impact on the echo SNR, thereby the sensing performance can be adjusted by controlling the dwell duration. For example, we can configure a long dwell duration when scanning a specified area to maximize the cumulative detection range or minimize the probability of false alarms. Generally, the sensing interval depends on the target kinematics and the desired tracking continuity and accuracy. In the scenario with high-speed moving targets, a relatively short sensing interval is required to prevent losing targets or large location error in tracking, while for the scenario with low-speed moving targets, too frequent sensing is unnecessary, and the sensing interval can be set relatively long to avoid waste of radio resources. Ignoring the practical sensing duration requirement and enabling simultaneous sensing and communication all the time during the ISAC service period may cause excessive sensing and waste of spectrum and energy, which may seriously degrade the overall system performance. Therefore, it is necessary to reasonably set the sensing duration according to the practical application requirements for unleashing the maximum potential of ISAC, especially in the resource-limited UAV-empowered networks.

Motivated by the above considerations, we study a UAV-empowered ISAC system that simultaneously provides communication services for multiple users and sensing services during the ISAC service period. Unlike the previous works that sensing and communication keep the same duration, in this work, we propose an adaptable ISAC (AISAC) mechanism that can flexibly configure the sensing duration according to the practical application requirements and enable sensing on demand during the communication rather than enabling sensing all the time, thus offering additional opportunities to improve the resource utilization and system performance. Our objective is to maximize the average system throughput by optimizing the communication and sensing beamforming as well as the UAV trajectory while guaranteeing the quality-of-service (QoS) requirements of communication and sensing. To efficiently solve this problem, we propose an efficient alternating optimization algorithm to find a high-quality solution. The main contributions of this paper are summarized as follows:

- We consider a UAV-empowered ISAC system, where the UAV communicates with multiple users and simultaneously performs sensing. To cater for different sensing duration requirements of different ISAC services and avoid potential resource waste and system performance degradation, we propose an AISAC mechanism that flexibly configures the sensing duration according to the practical application requirements and enables sensing on demand during the communication rather than enabling sensing all the time.
- Based on the proposed AISAC mechanism, we formulate an optimization problem to maximize the average system throughput by optimizing the communication and sensing beamforming as well as the UAV trajectory while guaranteeing the QoS requirements of communication and sensing. To efficiently solve the problem, we propose an alternating optimization algorithm that alternately optimizes the beamforming and UAV trajectory.
- By simulation, we validate that the proposed AISAC mechanism can significantly improve the average system throughput by flexibly configuring the sensing duration and enabling sensing on demand. Furthermore, the simulation results verified that the proposed alternating optimization algorithm can achieve a significant improvement on the average system throughput compared to the other benchmark schemes.

The rest of the paper is organized as follows. In Section II, we introduce the system model and the designed AISAC mechanism, and formulate the average system throughput maximization problem. In Section III, we propose an efficient alternating optimization algorithm to solve the formulated problem. In Section IV, we present the numerical results to validate the performance of the proposed algorithm. Finally, we conclude this work in Section V.

**Notations:** Boldface letters refer to vectors (lower) or matrices (upper). $A \succeq 0$ means that $A$ is positive semidefinite. $0$ denotes an all-zero vector or matrix. $I$ denotes an identity matrix. $\text{rank}(A)$ and $\text{tr}(A)$ denote the rank and trace of matrix $A$, respectively. The $(\cdot)^H$ denotes the conjugate transpose operator. $\| \cdot \|$ denote the magnitude of
a complex number and Euclidean norm, respectively. \( \mathbb{C} \) denotes the complex space. \( \mathcal{CN}(\mu, \Sigma) \) denotes the circularly symmetric complex Gaussian distribution with mean vector \( \mu \) and covariance matrix \( \Sigma \).

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a UAV-empowered AISAC system as shown in Fig. 1(a), in which the rotary-wing UAV flies from the predetermined initial location to the final location within an ISAC service period. At the end of period \( T \), the UAV needs to arrive at the final location (e.g., launch/landing sites) for some practical reasons, such as recharging or refueling. During the period \( T \), the UAV equipped with a vertically placed \( Q \)-antenna uniform linear array (ULA) communicates with \( K \) single-antenna ground user equipments (UEs) and simultaneously senses \( J \) targets on demand. The UAV performs sensing using its transmit signals, i.e., the UAV estimates the targets’ parameters based on the received echo signals that are transmitted by itself.

A. AISAC Time Slot Structure

For convenience, we divide the period \( T \) into \( N \) time slots with a slot length \( \tau = T/N \), which is indexed by \( n \in \{1, 2, \ldots, N\} \). Each time slot operates in a time division duplex (TDD) model and consists of the DL duration and UL duration, as illustrated in Fig. 1(b). In each time slot, the UAV performs communication procedures while adaptively enabling sensing according to the practical sensing requirements. For simplicity, we classify the services into two cases: communication only and ISAC. Specifically, in the former case, the UAV transmits the DL communication signals and receives the UL communication signals from UEs. In the latter case, the UAV transmits the ISAC signal to enable DL communication and sensing and receives the echoes reflected from the sensing targets besides the UL communication signals. The communication and sensing share the same ULA at the UAV, and the ISAC signal is a superimposition of individually precoded communication and sensing signals.

B. AISAC Mechanism

In practical sensing applications, too long sensing duration may result in unnecessary resource usage, while too short sensing duration may lead to the poor sensing performance. Therefore, it is necessary to develop an effective way to reasonably configure the sensing duration for improving the resource utilization and system performance. We define \( \psi_n \in \{0, 1\} \) as the sensing indicator at time slot \( n \), where \( \psi_n = 1 \) indicates that the UAV performs sensing during the DL communication to enable ISAC, while \( \psi_n = 0 \) means that the UAV only enables DL communication. In such settings, the unit of the sensing duration is set as the same with that of the DL communication. Therefore, the sensing duration can be configured by setting the value of \( \psi_n \). For example, if a longer sensing duration is intended, the sensing indicator of more time slots should be set to 1.

In the following, we propose a novel AISAC mechanism that determines \( \psi_n \) according to the variations of sensing-related parameter. Specifically, we use a ratio \( f_{mv}^n \) to characterize the parameter difference between the \((m - 1)\)-th sensing and \(m\)-th sensing, i.e.,

\[
f_{mv}^n = \frac{\zeta_m - \zeta_{m-1}}{\zeta_{m-1}},
\]

where \( \zeta_m \) denotes the sensing-related parameter of the \(m\)-th sensing, such as the target moving speed, or error/mean squared error (MSE) of the target speed/location estimation [14], [18], which can be obtained by performing sensing at the UAV. The obtained sensing-related parameter can be used to guide the setting of the sensing duration in the future ISAC service period. When the target moving speed, or error/MSE of the target speed/location estimation of the \(m\)-th sensing becomes large, accordingly, \( f_{mv}^n \) will become large, and then we can configure a long sensing duration to prevent losing targets or large estimation error/MSE in tracking [19]. When the target moving speed, or error/MSE of the target speed/location estimation is small, too long sensing duration is unnecessary, and the sensing duration can be set relatively short to avoid waste of radio resources. \( f_{mv}^n \) reflects the demand level of the sensing duration, thus it can be applied to guide the setting of \( \psi_n \). The smaller/larger the \( f_{mv}^n \), the shorter/longer the required sensing duration, and the larger/smaller the sensing interval. For the given period \( T \), the larger the sensing interval, the smaller the total sensing duration. By setting a threshold, denoted by \( f_{th}^n \), for \( f_{mv}^n \) the sensing interval can be configured. Specifically, when \( f_{mv}^n \) is smaller/greater than \( f_{th}^n \), we can increase/decrease, such as in exponentially, the sensing interval, thereby allowing higher sensing flexibility compared to the fixed sensing interval. Considering that the ever increasing of the sensing interval may lead to the loss of tracked targets or missing detection of new targets, a maximum value, denoted by \( \Delta_{max} \), needs to be set for the sensing interval to prevent it becoming too large. Similarly, a minimum value \( \Delta_{min} \) also needs to be set to prevent the ever decreasing of the sensing interval. The proposed AISAC mechanism is summarized in Algorithm 1.

C. Transmit Signal Model

Communication and sensing usually have different performance requirements for waveforms. For example, communication waveforms are expected to achieve a high data rate, while sensing waveforms are desired to have properties of the constant envelope and good correlation. Therefore, in this work, we use different waveforms for communication and sensing. During the DL stage, the transmit signal of the UAV at time slot \( n \) is expressed as

\[
x_{DL}^{k,n} = \sum_{j=1}^{N} w_{k,n} s_{k,n}^{sens} + \psi_n \sum_{j=1}^{N} r_{j,n} s_{j,n}^{sens},
\]

where \( w_{k,n} \in \mathbb{C}^{Q \times 1} \) and \( r_{j,n} \in \mathbb{C}^{Q \times 1} \) are the transmit beamforming vectors for DL communication and sensing, respectively. \( s_{k,n}^{sens} \sim \mathcal{CN}(0, 1) \) and \( s_{j,n}^{sens} \) are the uncorrelated communication signal and dedicated sensing signal, respectively. The elements of \( \{s_{k,n}^{sens}, \forall j\} \) are independent and each of which has zero mean and unit variance. During the UL stage, the transmit signal of UE \( k \) is

\[
x_{k,n} = \sqrt{p_k} s_{k,n}^{UL},
\]

where \( p_k \) denotes the transmit power and \( s_{k,n}^{UL} \sim \mathcal{CN}(0, 1) \) is the communication signal.
the propagation environment such as rural, urban, or dense

D. Receive Signal Model

We consider a three-dimensional (3D) Cartesian coordinate system, in which the horizontal coordinates of the UE k, the target j and the UAV at time slot n are \( q_{k,n} = (x_k, y_k) \), \( q_{j,n} = (x_{j,n}, y_{j,n}) \) and \( q_n = (x_n, y_n) \), respectively. For convenience, the 3D UAV trajectory within the period \( T \) is represented by \( \{(q_n, z_n), \forall n\} \), where \( z_n \) denotes the altitude of the UAV. We assume the probabilistic LoS channel model for all communication and sensing channels. The LoS occurrence probability between the UAV and UE k or target j at time slot n can be modeled as [20]

\[
P_{m \in \{k, j\}, n}^{\text{LoS}} = \frac{1}{1 + C \exp(-D(\theta_{m,n} - C))},
\]

where \( C \) and \( D \) are the constant parameters depending on the propagation environment such as rural, urban, or dense.

Algorithm 1 Adaptable ISAC Mechanism

\begin{algorithm}
\KwIn{\( m = 1 \) and \( \zeta_{m-1} \).

\Repeat{\( m = m + 1 \)}{
\text{Compute} \quad f_{m}^{\text{PV}} = \frac{\zeta_{m} - \zeta_{m-1}}{\zeta_{m-1}};
\If{\( f_{m}^{\text{PV}} \leq f_{0}^{\text{PV}} \)}{
\text{Increase the sensing interval to} \Delta_{m}, \text{and then the implemented sensing interval is}
\Delta_{m} = \min\{\Delta_{m}, \Delta_{\text{max}}\};
\Else{
\text{Decrease the sensing interval to} \Delta_{m}, \text{and then the implemented sensing interval is}
\Delta_{m} = \max\{\Delta_{m}, \Delta_{\text{min}}\};
}
\text{The configuration of the sensing interval within the period} T \text{is obtained.}
}
\KwOut{The configuration of the sensing interval and the setting of the sensing indicator} \psi_{n}.
\end{algorithm}

urban, \( \theta_{m,n} = \frac{180}{\pi} \arcsin \left( \frac{z_n}{d_n} \right) \) is the elevation angle, and \( d_{m,n} = \sqrt{x_n^2 + \|q_n - q_{m,n}\|^2} \) is the distance between the UAV and UE k or target j. Accordingly, the non-LoS (NLoS) occurrence probability is \( P_{m,n}^{\text{NLoS}} = 1 - P_{m,n}^{\text{LoS}} \).

1) Communication Receive Signal Model: The path loss of the UE-UAV link for the LoS and NLoS conditions can be modeled by \( \beta_{0}d_{k,n}^{-2} \) and \( \kappa\beta_{0}d_{k,n}^{-2} \), respectively. \( \beta_{0} \) denotes the channel power gain at a reference distance \( d_0 = 1 \) m. \( \kappa < 1 \) is the additional attenuation factor due to the NLoS condition. We assume that the DL and UL channels are reciprocal. In addition, the Doppler shifts caused by the movement of the UAV are assumed to be constant during one time slot and can be completely compensated [21]. Let \( h_{k,n}^{\text{DL}} (\Xi \in \{\text{DL, UL}\}) \) denote the wireless channel between the UAV and UE k at time slot n, which is given by

\[
h_{k,n}^{\Xi} = \sqrt{P_{k,n}^{\text{LoS}}(\beta_{0}d_{k,n}^{-2})}h_{k,n}^{\text{LoS}} + \sqrt{P_{k,n}^{\text{NLoS}}(\kappa\beta_{0}d_{k,n}^{-2})}h_{k,n}^{\text{NLoS}},
\]

where \( h_{k,n}^{\text{LoS}} = a_{k,n} \), \( a_{k,n} = [1, e^{-j2\pi d\sin \theta_{k,n}}, \ldots, e^{-j2\pi(Q-1)\sin \theta_{k,n}}]^T \) denotes the transmit steering vector, \( d \) is the antenna separation, and \( \lambda \) is the carrier wavelength. The NLoS component \( h_{k,n}^{\text{NLoS}} \) is the complex Gaussian random vector with zero mean and unit covariance matrix.

The signal received by the UE k and the combined signal at the UAV can be respectively written as

\[
y_{k,n}^{\text{DL}} = (h_{k,n}^{\text{DL}})^Hw_{k,n}s_{k,n}^{\text{DL}} + \sum_{i \neq k} (h_{k,n}^{\text{DL}})^Hw_{i,n}s_{i,n}^{\text{DL}} + \psi_{n}\sum_{j=1}^{J} (h_{j,n}^{\text{DL}})^Hr_{j,n} + n_{k,n}^{\text{DL}},
\]

(4)

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where $\mathbf{v}_{k,n} \in \mathbb{C}^{2 \times 1}$ is the unit-norm receive beamforming vector, $\mathbf{h}_{\text{DL}}^{k,n} \sim \mathcal{CN}(0, \sigma_{\text{DL}}^{2})$ and $\mathbf{n}_{\text{AWGN}}^{k,n} \sim \mathcal{CN}(0, \sigma_{\text{UL}}^{2})$ are the additive white Gaussian noise (AWGN) at UE $k$ and at the UAV, respectively. $\xi_{n} \in \{0, 1\}$ is the signal overlapping indicator, where $\xi_{n} = 1$ indicates that the UL communication signals are overlapped with the echos, otherwise $\xi_{n} = 0$. Note that $\xi_{n} = 0$ holds if $\psi_{n} = 0$.

The SINR of DL communication and UL communication for UE $k$ can be respectively computed by

$$\gamma_{k,n}^{\text{DL}} = \frac{|\mathbf{h}_{\text{DL}}^{k,n}^{H} \mathbf{w}_{k,n}|^2}{I_{k,n}^{\text{DL}} + \sigma_{\text{DL}}^{2}},$$

$$\gamma_{k,n}^{\text{UL}} = \frac{p_{k} |\mathbf{v}_{k,n}^{H} \mathbf{h}_{\text{UL}}^{k,n}|^2}{I_{k,n}^{\text{UL}} + \sigma_{\text{UL}}^{2}},$$

where $I_{k,n}^{\text{DL}} = \sum_{j=1}^{J} |\mathbf{h}_{\text{DL}}^{j,n}^{H} \mathbf{w}_{k,n}|^2 + \psi_{n} \sum_{j=1}^{J} |\mathbf{h}_{\text{DL}}^{j,n}^{H} \mathbf{r}_{j,n}|^2$ and $I_{k,n}^{\text{UL}} = |\mathbf{v}_{k,n}^{H} \mathbf{h}_{\text{UL}}^{k,n}|^2$ represent the co-channel interference for DL and UL, respectively. Then, the DL and UL throughput in bit/s/Hz for UE $k$ at time slot $n$ can be respectively computed by

$$R_{k,n}^{\text{DL}} = t_{n}^{\text{DL}} \log_{2} (1 + \gamma_{k,n}^{\text{DL}}),$$

$$R_{k,n}^{\text{UL}} = \frac{t_{n}^{\text{UL},1}}{2} \log_{2} \left( 1 + \gamma_{k,n}^{\text{UL}} \right) + \frac{t_{n}^{\text{UL},2}}{2} \log_{2} \left( 1 + \gamma_{k,n}^{\text{UL}} \right),$$

where $t_{n}^{\text{DL}}$ denotes the DL duration, $t_{n}^{\text{UL},1}$ and $t_{n}^{\text{UL},2}$ denote the UL duration when $\xi_{n} = 1$ and $\xi_{n} = 0$, respectively. Note that when no echo interference in time slot $n$, i.e., $\psi_{n} = 0$, $t_{n}^{\text{UL},1} = 0$ and $t_{n}^{\text{UL},1} \log_{2} \left( 1 + \gamma_{k,n}^{\text{UL}} \right) = 0$ hold. $\gamma_{k,n}^{\text{UL}}|_{\xi_{n}=1}$ and $\gamma_{k,n}^{\text{UL}}|_{\xi_{n}=0}$ denote the SINR conditioned on $\xi_{n} = 1$ and $\xi_{n} = 0$, respectively.

2) Sensing Receive Signal Model: The signals transmitted by the UAV are reflected from the targets and then received by the UAV. The Doppler shifts caused by the movement of targets and UAV are assumed to be constant during one time slot and can be well compensated [21]. The sensing channel of the target $j$ can be modeled as

$$\mathbf{G}_{j,n} = \alpha_{j,n}^{\text{Sens}} \sqrt{p_{\text{LoS}}^{j,n}} \mathbf{G}_{\text{LoS}}^{j,n} + \alpha_{j,n}^{\text{NLoS}} \sqrt{p_{\text{NLoS}}^{j,n}} \mathbf{G}_{\text{NLoS}}^{j,n},$$

where $\alpha_{j,n}^{\text{Sens}} = \frac{\sigma_{\text{Sens}}}{2 \pi}$ is the complex reflection coefficient, $\sigma_{\text{Sens}}$ represents the complex radar cross-section (RCS) [22], [23]. $\mathbf{G}_{\text{LoS}}^{j,n}$ is the LoS signal, and $\mathbf{G}_{\text{NLoS}}^{j,n}$ denotes the transmit steering vector. The entries of $\mathbf{G}_{\text{LoS}}^{j,n}$ are complex Gaussian random variables with zero mean and unit variance.

The communication signals interfere the reflected echoes, which degrades the sensing performance. To improve the sensing performance, we propose that the UAV extracts sensing signals by subtracting the known DL communication signals and the decoded UEs’ signals from the received signals. Note that the self-interference caused by simultaneous transmission and reception during sensing is assumed to be cancelled by employing proper self-interference cancellation methods. Therefore, the received reflected echo signals at the UAV can be expressed as

$$y_{n}^{\text{Sens}} = \sum_{j=1}^{J} \mathbf{G}_{j,n} \mathbf{r}_{j,n} + \mathbf{n}_{\text{UAV}}^{n}.$$}

After receiving the reflected echo signals, the UAV needs to estimate the unknown parameters, i.e., the reflection coefficient $\alpha_{j,n}^{\text{Sens}}$ and the AoD angle $\theta_{j,n}$. Since it is difficult to extract the target information from $\alpha_{j,n}^{\text{Sens}}$, we focus on the estimation of $\theta_{j,n}$. For the parameter estimator in radar sensing, Cramér-Rao bound (CRB) is an important sensing performance measure, which could provide a lower bound for the MSE of parameter estimators [24]. According to [25], the CRB for estimating $\theta_{j,n}$ when given other targets’ directions is expressed as

$$\text{CRB}(\theta_{j,n}) = \frac{\sigma_{\text{UAV}}^{2}}{2 |\alpha_{j,n}^{\text{Sens}}|^{2} (\text{tr}(\mathbf{B}_{j,n}^{H} \mathbf{B}_{j,n} \mathbf{r}_{j,n}^{H} \mathbf{r}_{j,n}^{H})))},$$

where $\mathbf{B}_{j,n} = \frac{\partial \mathbf{B}_{j,n}}{\partial \theta_{j,n}}$ denotes the partial derivative of $\mathbf{B}_{j,n}$ with respect to $\theta_{j,n}$, and $\mathbf{B}_{j,n} = \sqrt{p_{\text{LoS}}^{j,n}} \mathbf{G}_{\text{LoS}}^{j,n} + \sqrt{p_{\text{NLoS}}^{j,n}} \mathbf{G}_{\text{NLoS}}^{j,n} \mathbf{r}_{j,n}^{H}$.

E. UAV Energy Model

The UAV energy consumption consists of two main components, i.e., the communication and sensing energy and the flight energy. The communication and sensing energy of the UAV at time slot $n$ is given by

$$E_{\text{ISAC}}^{n} = t_{n}^{\text{DL}} \left( \sum_{k=1}^{K} \| \mathbf{w}_{k,n} \|^2 + \sum_{j=1}^{J} \psi_{n} \| \mathbf{r}_{j,n} \|^2 \right).$$

According to the classical aircraft dynamics of the rotary-wing UAV [26], the aerodynamic energy consumption of the UAV at time slot $n$ can be modeled as

$$E_{n}^{\text{Fly}} = \left\{ P_{0} \left( 1 + \frac{3(V_{n}^{xy})^{2}}{U_{\text{tip}}^{2}} \right) + P_{1} \left( \sqrt{1 + \frac{(V_{n}^{xy})^{2}}{4V_{0}^{2}}} - \frac{(V_{n}^{xy})^{2}}{2V_{0}^{2}} \right) + C_{0} (V_{n}^{xy})^{3} + G_{0} V_{n}^{2} \right\} \tau,$$

where $P_{0}$, $P_{1}$, $U_{\text{tip}}$, $V_{0}$, and $C_{0}$ are constant parameters related to aerodynamics, and $G_{0}$ is the weight of the UAV. $V_{n}^{xy} = \sqrt{x_{n}^{2} + y_{n}^{2} - z_{n}^{2} + 1}$ and $V_{n}^{z} = \sqrt{x_{n}^{2} + y_{n}^{2} - z_{n}^{2} + 1}$ are the horizontal and vertical speeds of the UAV, respectively, which are assumed to be constant during each time slot.

F. Problem Formulation

In the UAV-empowered AISAC system, we define the average system throughput as the sum of the average DL and
UL throughput over $N$ time slots, i.e., $\frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} (R_{DL}^{k,n} + R_{UL}^{k,n})$. We aim to maximize the average system throughput by jointly optimizing the communication and sensing beamforming \{\{w_{k,n}, v_{k,n}, r_{j,n}, \forall k, j, n\}\} as well as the UAV trajectory $S = \{\{(q_n, z_n), \forall n\}\}$ subject to the QoS requirements of communication and sensing, UAV energy limit, UAV transmit power budget, and UAV location constraints. By applying the proposed AISAC mechanism, the setting of the sensing power budget, and UAV location constraints. By applying the proposed AISAC mechanism, the setting of the sensing power budget, and UAV location constraints.

Therefore, the optimization problem is formulated as

$$\mathbf{P}_0 : \ \max_{\{w_{k,n}, v_{k,n}, r_{j,n}, \forall k, j, n\}} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} (R_{DL}^{k,n} + R_{UL}^{k,n})$$

subject to

\begin{align}
&\psi_n \leq \psi_n^{Sens} \gamma_{th}^s, \quad \forall j, n, & (15a) \\
&\gamma_{k,n}^{DL} \geq \gamma_{th}^{DL}, \quad \forall k, n, & (15b) \\
&\gamma_{k,n}^{UL} \geq \gamma_{th}^{UL}, \quad \forall k, n, & (15c) \\
&\left\|w_{k,n}\right\|^2 + \psi_n \sum_{j=1}^{J} \left\|r_{j,n}\right\|^2 \leq P_{n,\psi_{n}}^{max}, \quad \forall n, & (15d) \\
&\sum_{n=1}^{N} E_{ISAC}^n + \sum_{n=1}^{N} E_{Fly}^n \leq E_{UV}, & (15e) \\
&\left\|v_{k,n}\right\|^2 = 1, \quad \forall k, n, & (15f) \\
&\left\|q_{n+1} - q_{n}\right\| \leq V_{xy_{max}}, \quad \forall n, & (15g) \\
&z_{n} \leq z_{n+1} \leq z_{max}, \quad \forall n, & (15h) \\
&(q_1, z_1) = (q_{F}, z_{F}), (q_{N}, z_{N}) = (q_{F}, z_{F}), & (15i)
\end{align}

where constraint (15a) shows that the CRB needs to be smaller than a given threshold $\psi_n^{Sens}$ to guarantee the sensing performance. Constraints (15b) and (15c) describe the QoS requirements of DL and UL communication, respectively. Constraint (15d) indicates that the transmit power budget of the UAV is $P_{n,\psi_{n}}^{max}$. Constraint (15e) represents the energy limit of the UAV. Constraint (15f) is the unit norm constraint of the receive beamforming vector. Constraints (15g) and (15h) describe the maximum horizontal and vertical flying speed limits, respectively, where $V_{xy_{max}}$ is the maximum horizontal flying speed and $V_{z_{max}}$ is the maximum vertical flying speed. Constraint (15i) restricts the altitude of the UAV. The minimum altitude $z_{min}$ and the maximum altitude $z_{max}$ may be imposed by government regulation [27]. In constraint (15i), $q_{F}$ and $q_{F}$ are the initial and final horizontal locations, respectively, and $z_{F}$ and $z_{F}$ are the initial and final altitudes, respectively.

### III. PROPOSED ALTERNATING OPTIMIZATION ALGORITHM

Problem $\mathbf{P}_0$ is difficult to be solved optimally due to the non-concave objective function and constraints. When given the UAV’s trajectory $S$, the beamforming variables $\{w_{k,n}, v_{k,n}, r_{j,n}, \forall k, j, n\}$ are highly coupled. In addition, even though the beamforming variables are fixed, problem $\mathbf{P}_0$ with respect to $S$ is still difficult to be solved optimally since the trajectory variables $\psi_{n}$ are involved in the channel vectors in an extraordinarily complicated form according to (3) and (10). Therefore, considering the highly coupling of the beamforming variables and highly difficulty of directly optimizing the UAV trajectory, we propose an alternating optimization algorithm by alternately optimizing the communication and sensing beamforming as well as the UAV trajectory to find the suboptimal solution.

#### A. Transmit and Receive Beamforming Design

In this subsection, we focus on the beamforming optimization for a given UAV trajectory $S$. In other words, for the given $S$, we optimize $\{w_{k,n}, v_{k,n}, r_{j,n}, \forall k, j, n\}$, which corresponds to solving the following problem

$$\mathbf{P}_1 : \ \max_{\{w_{k,n}, v_{k,n}, r_{j,n}, \forall k, j, n\}} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} (R_{DL}^{k,n} + R_{UL}^{k,n})$$

subject to

\begin{align}
&\psi_n \leq \psi_n^{Sens} \gamma_{th}^s, \quad \forall j, n, & (17a) \\
&p_{k} \psi_n \leq 1, \quad \forall k, n, & (17b) \\
&\sum_{k=1}^{K} \psi_n \sum_{j=1}^{J} \psi_j \leq P_{n,\psi_{n}}^{max}, \quad \forall n, & (17c) \\
&\sum_{n=1}^{N} E_{ISAC}^n + \sum_{n=1}^{N} E_{Fly}^n \leq E_{UV}, & (17d) \\
&\sum_{n=1}^{N} E_{Fly}^n \leq E_{UV}, & (17e) \\
&W_{k,n}, v_{k,n}, r_{j,n}, \forall n, & (17f) \\
&\psi_n \psi_j \leq 1, \quad \forall k, j, n, & (17g) \\
&\text{rank}(W_{k,n}) = \text{rank}(V_{k,n}) = 1, \quad \forall n, & (17h)
\end{align}

Then, problem $\mathbf{P}_1$ is recast as the following problem

$$\mathbf{P}_2 : \ \max_{z} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} \left(\Omega_{DL}^{k,n}(Z) + \Omega_{UL}^{k,n}(Z) + \Omega_{UL}^{k,n}(Z)\right)$$

subject to

\begin{align}
&\psi_n \psi_j \leq 1, \quad \forall k, j, n, & (19a) \\
&\sum_{n=1}^{N} E_{ISAC}^n + \sum_{n=1}^{N} E_{Fly}^n \leq E_{UV}, & (19b) \\
&W_{k,n}, v_{k,n}, r_{j,n}, \forall n, & (19c) \\
&\psi_n \psi_j \leq 1, \quad \forall k, j, n, & (19d) \\
&\text{rank}(W_{k,n}) = \text{rank}(V_{k,n}) = 1, \quad \forall n, & (19e)
\end{align}

Therefore, problem $\mathbf{P}_2$ can be solved by an alternating optimization algorithm.
where $\mathcal{Z} = \{W_{k,n}, V_{n,r,j}, R_{r,j,n} \forall j, n\}$, $H_{k,n}^{DL} = h_{k,n}^{DL}(h_{k,n}^{DL})^H$, $H_{k,n}^{UL} = h_{k,n}^{UL}(h_{k,n}^{UL})^H$, $Q_{k,n}^{DL}(Z) = t_n^{DL} \log(1 + \frac{\rho_n \text{tr}(\hat{H}_{k,n}^{DL} W_{n,r})}{\Phi_{k,n}^{DL}(Z)}), \Omega_{k,n}^{DL}(Z) = t_n^{UL,1} \log(1 + \frac{\rho_n \text{tr}(\hat{H}_{k,n}^{UL} V_{n,r,j})}{\Phi_{k,n}^{UL}(Z)}), H_{k,n}^{UL} = h_{k,n}^{UL}(h_{k,n}^{UL})^H$, $Q_{k,n}^{UL}(Z) = t_n^{UL,1} \log(1 + \frac{\rho_n \text{tr}(\hat{H}_{k,n}^{UL} V_{n,r,j})}{\Phi_{k,n}^{UL}(Z)}))$.

$P_5$ is fixed, the optimal $\delta^*$ is obtained by setting the derivative of the objective function with respect to $\delta$ to zero, which is given as

$$\delta_{k,n}^* = \frac{\text{tr}(H_{k,n}^{DL} W_{k,n})}{\Phi_{k,n}^{DL}(Z)}, \delta_{k,n}^* = \frac{\text{tr}(H_{k,n}^{UL} V_{n,r,j})}{\Phi_{k,n}^{UL}(Z)}.$$

Then, we apply the quadratic transform method [28] to equivalently translate problem $P_4$ into a more tractable form

$$P_5 : \max_{W, \delta, \epsilon} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} \left( t_n^{DL} \left( \log(1 + \delta_{k,n}^{DL}) - \delta_{k,n}^{DL} \right) + 2\epsilon_{k,n}^{DL} \right) \sqrt{C_{DL}^{UL} - (\epsilon_{k,n}^{UL})^2 D_{DL}^{UL} + t_n^{UL,1}} \times \left( \log(1 + \gamma_{k,n}^{UL}) - \gamma_{k,n}^{UL} \right) + 2\epsilon_{k,n}^{UL} \sqrt{C_{UL}^{UL} - (\epsilon_{k,n}^{UL})^2 D_{UL}^{UL}}$$

s.t. (17b) - (17e), (18a), (18b), (18c).

In problem $P_5$, for fixed $\delta$ and $\epsilon$, the objective function with respect to $W$ is concave. However, problem $P_5$ is still non-convex due to the non-convex rank constraints in (18c). We relax the rank constraints, so that problem $P_5$ over $W$ becomes a standard convex optimization problem, which can be solved optimally by CVX. For the rank constraints, when there is no guarantee that the obtained optimal $W^*$ is of rank-one, the Gaussian randomization technique [29] can be utilized to obtain an approximated solution that satisfies the rank-one constraints. Fortunately, by checking the Karush-Kuhn-Tucker (KKT) optimality conditions of the relaxed version of problem $P_5$ and applying the similar analysis as in the Appendix of [30] and [31], it can be found that there always exists an optimal rank-one solution $W^*$, and thus the Gaussian randomization is not needed for solving problem $P_5$. The detailed proof is omitted due to space limitations.

2) Receive Beamforming Design for UL Communication: For given $W$, $R$, and $S$, problem $P_2$ over $V$ can be formulated as

$$P_6 : \max_{V} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} \left( \Omega_{k,n}^{DL}(Z) + \Omega_{k,n}^{UL,1}(Z) \right)$$

s.t. (17c), (23a)

$$V_{k,n} \succeq 0, \forall k, n,$$

$$\text{tr}(V_{k,n}) = 1, \forall k, n,$$

$$\text{rank}(V_k) = 1, \forall k.$$
Algorithm 2 Transmit Beamforming Design for DL Communication

Input: \( W^0 \), iteration number \( l_1 = 1 \), and maximum iteration number \( l_1^{\text{max}} \).

1 repeat
2 Given \( W(l_1-1) \), update the auxiliary variables \( \delta(l_1) = \{\delta_{k,n}(l_1), \delta^U_{k,n}(l_1), \forall k, n\} \);
3 Given \( W(l_1-1) \) and \( \delta(l_1) \), update the auxiliary variables \( \epsilon(l_1) = \{\epsilon_{k,n}(l_1), \epsilon^U_{k,n}(l_1), \forall k, n\} \);
4 Given \( \delta(l_1) \) and \( \epsilon(l_1) \), update the optimization variable \( W(l_1) \);
5 \( l_1 = l_1 + 1 \);
6 until The objective function value converges or \( l_1 > l_1^{\text{max}} \);

Output: \( W^* \).

3) Transmit Beamforming Design for Sensing: In problem \( P_2 \), the transmit beamforming for sensing is required if and only if the UAV decides to enable sensing. For given \( W \), \( V \), and \( S \), problem \( P_2 \) over \( R \) can be reformulated as

\[
\max_{R} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} \left( \Omega^{DL}_{k,n}(Z) + \Omega^{UL,1}_{k,n}(Z) \right)
\]

s.t. \((17a) - (17e)\), \((24b)\), \((24c)\).

Although \( W \) and \( V \) are fixed, problem \( P_7 \) is still non-convex due to the non-concave objective function and the rank-one constraints. To tackle this non-convex problem, we introduce auxiliary variables \( \chi = \{\chi^{DL}_{k,n} = \text{tr}(H^{DL}_{k,n}W_{k,n})/\Phi^{DL}_{k,n}(Z), \chi^{UL}_{k,n} = p_k \text{tr}(H^{UL}_{k,n}V_{k,n})/\Phi^{UL}_{k,n}(Z), \forall k, n\} \), and then transform problem \( P_7 \) into the following problem

\[
\max_{R, \chi} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} \left( t^{DL}_n \log(1 + \chi^{DL}_{k,n}) + t^{UL,1}_n \log(1 + \chi^{UL}_{k,n}) \right)
\]

s.t. \((17a) - (17e)\), \((24b)\), \((24c)\), \((25c)\).

Before solving problem \( P_8 \), we rewrite the constraints \((25b)\) and \((25c)\) as

\[
\text{tr}(H^{DL}_{k,n}W_{k,n}) \geq \chi^{DL}_{k,n}, \forall k, n,
\]

\[
p_k \text{tr}(H^{UL}_{k,n}V_{k,n}) \geq \chi^{UL}_{k,n}, \forall k, n.
\]

Since the right hand terms in inequalities \((26)\) and \((27)\) are quasi-concave, the constraints \((26)\) and \((27)\) are still non-convex. To deal with these non-convex constraints, we invoke the convex upper bound approximation method \([32]\) and transform the constraints \((26)\) and \((27)\) into

\[
\text{tr}(H^{DL}_{k,n}W_{k,n}) \geq \frac{\left(\Phi^{DL}_{k,n}(Z)\right)^2}{2 \Omega^{DL}_{k,n}}, \forall k, n,
\]

\[
p_k \text{tr}(H^{UL}_{k,n}V_{k,n}) \geq \frac{\left(\Phi^{UL}_{k,n}(Z)\right)_{\xi_n=1}^2}{2 \Omega^{UL}_{k,n}}, \forall k, n,
\]

where the right hand terms in inequalities \((28)\) and \((29)\) are convex. Equalities in inequations \((28)\) and \((29)\) will always hold if \( \Omega^{DL}_{k,n} = \Phi^{DL}_{k,n}(Z)/\chi^{DL}_{k,n}, \Omega^{UL}_{k,n} = \Phi^{UL}_{k,n}(Z)/\chi^{UL}_{k,n}, \) where \( \Lambda \in \{\text{DL, UL}\} \).

Algorithm 3 Transmit Beamforming Design for Sensing

Input: \( R^0, \chi^0 \), iteration number \( l_2 = 1 \), and maximum iteration number \( l_2^{\text{max}} \).

1 repeat
2 Given \( R(l_2-1) \) and \( \chi(l_2-1) \), compute \( \Theta^{(l_2)} = \{\Theta^{DL}_{k,n}(l_2), \Theta^{UL}_{k,n}(l_2), \forall k\} \);
3 Given \( \Theta^{(l_2)} \), update \( R^{(l_2)} \) and \( \chi^{(l_2)} \);
4 \( l_2 = l_2 + 1 \);
5 until The objective function value converges or \( l_2 > l_2^{\text{max}} \);

Output: \( R^* \).

It is noted that after relaxing the non-convex rank-one constraints \((24c)\), problem \( P_9 \) is convex with respect to \( R \) and \( \chi \), which can be solved efficiently by the proposed optimization method summarized in Algorithm 3. By checking the KKT optimality conditions of the relaxed version of problem \( P_9 \), the optimal \( R^* \) is of rank-one.

B. UAV Trajectory Optimization

For fixed beamforming designs \( \{w_{k,n}, v_{k,n}, r_{j,n}, \forall k, j, n\} \), we can express problem \( P_0 \) as

\[
\max_{S} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} (R^{DL}_{k,n} + R^{UL}_{k,n})
\]

s.t. \((15a) - (15c), (15e), (15g) - (15j)\).

Problem \( P_{10} \) is challenging to solve due to the non-concave objective function and the non-convex constraints. It can be seen from \((3)\) and \((10)\) that the transmit steering vector \( a^{k,n} \) is challenging to solve due to the non-concave objective function and the non-convex constraints. It can be seen from \((3)\) and \((10)\) that the transmit steering vector \( a^{k,n} \)
and $b_{j,n}$ are complicated and non-linear with respect to the UAV trajectory variables, which makes the UAV trajectory design become very difficult. To make the trajectory design more tractable, we use the UAV trajectory of the $l$-th iteration to approximate $\alpha_{k,n}$ and $b_{j,n}$ in the $(l+1)$-th iteration [33].

As a result, the approximate communication channel $\tilde{h}^e_{k,n}$ and sensing channel $\tilde{G}_{j,n}$ are given as

$$
\tilde{h}^e_{k,n} = d_{k,n}^{-1} \left( (P_{L0S}^e(l))^{1/0} \left( h_{k,n}^e \right)^{1/0} \right)
+ \sqrt{(P_{L0S}^e(l))^{1/0} \left( G_{j,n}^e \right)^{1/0}} = d_{k,n}^{-1} \tilde{h}_{k,n}, \quad \forall k, n,
$$

$$
\tilde{G}_{j,n} = d_{j,n}^{-1/2} \left( (P_{L0S}^e(l))^{1/0} \left( G_{j,n} \right)^{1/0} \right)
+ \sqrt{(P_{L0S}^e(l))^{1/0} \left( K_{j,n}^e \right)^{1/0} \left( G_{j,n}^e \right)^{1/0}} = d_{j,n}^{-1} \tilde{H}_{j,n}, \quad \forall j, n,
$$

where $(h_{k,n}^e)^{1/0}$, $(G_{j,n})^{1/0}$, $(h_{k,n}^e)^{1/0}$, $(G_{j,n})^{1/0}$, $(P_{L0S}^e(l))^{1/0}$,

For notational simplicity, the objective function in problem $\mathbf{P}_{10}$ can be recast as

$$
\frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} \left( \tilde{d}_n^T \Gamma_{k,n} + \tilde{d}_n^T \Gamma_{k,n} \xi_n = 1 + \tilde{d}_n^T \Gamma_{k,n} \xi_n = 0 \right),
$$

where $\Gamma_{k,n}$ is convex with respect to $\xi_n$ and $\Gamma_{k,n} = 0$, respectively. In this new objective function, $\Gamma_{DL,k,n}$ and $\Gamma_{UL,k,n}$ are given as

$$
\Gamma_{DL,k,n} = \tilde{\Gamma}_{DL,k,n} - \log_2 \left( \frac{1}{s_{k,n}} + \sigma_2^{DL} \right), \forall k, n,
$$

$$
\Gamma_{UL,k,n} = \tilde{\Gamma}_{UL,k,n} - \log_2 \left( \sum_{i=1}^{K} F_{k,n} \xi_n + \xi_n \right), \forall k, n
$$

where $\tilde{\Gamma}_{DL,k,n} = \log_2 \left( \frac{\epsilon_{DL}^{\text{low}} + \epsilon_{DL}^{\text{high}}}{s_{k,n}} + \sigma_2^{DL} \right)$, $\tilde{\Gamma}_{UL,k,n} = \log_2 \left( \frac{1}{s_{k,n}} + \sum_{i=1}^{K} F_{k,n} \xi_n + \sigma_1^{DL} \right)$, $s_{k,n} = z_n^2 + \|q_n - q_n\|^2$, $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$, $\epsilon_{UL} = \epsilon_{k,n}^{UL} w_{k,n}^2$, $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$, $\epsilon_{UL} = \epsilon_{k,n}^{UL} w_{k,n}^2$, $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$, $\epsilon_{UL} = \epsilon_{k,n}^{UL} w_{k,n}^2$.

$\tilde{\Gamma}_{k,n}$ is non-convex with respect to $q_n$ and $z_n$, but it is convex with respect to $s_{k,n}$. Since the first-order Taylor expansion serves as the global lower bound of a convex function, we can obtain the following lower bound for $\tilde{\Gamma}_{DL,k,n}$ at the given point $s_{k,n} = (z_n^2 + \|q_n - q_n\|^2)^{1/0}$

$$
\tilde{\Gamma}_{DL,k,n} \geq \log_2 \left( \frac{\epsilon_{DL} + \epsilon_{DL} + \epsilon_{DL}^{\text{low}}}{s_{k,n} + \epsilon_{DL}^{\text{low}}} + \sigma_2^{DL} \right).
$$

Since $s_{k,n}$ is convex with respect to $q_n$ and $z_n$, $\tilde{\Gamma}_{DL,k,n}$ is concave with respect to $q_n$ and $z_n$. After substituting $\tilde{\Gamma}_{DL,k,n}$ with $\tilde{\Gamma}_{DL,k,n}^{\text{low}}$, we can get

$$
\tilde{\Gamma}_{DL,k,n} = \tilde{\Gamma}_{DL,k,n}^{\text{low}} - \log_2 \left( \frac{\epsilon_{DL}^{\text{low}} + \epsilon_{DL}^{\text{low}}}{s_{k,n} + \epsilon_{DL}^{\text{low}}} + \sigma_2^{DL} \right),
$$

where $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$, $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$, $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$, $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$, $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$, $\epsilon_{DL} = \epsilon_{k,n}^{DL} w_{k,n}^2$.

Based on the above processing, problem $\mathbf{P}_{10}$ can be converted into the following problem $\mathbf{P}_{11}$

$$
\max_{\{s_{k,n}, \eta_n, \xi_n, j,n \}} \sum_{n=1}^{N} \sum_{k=1}^{K} \left( \frac{d_n^T \Gamma_{k,n} + d_n^T \Gamma_{k,n} \xi_n = 1 + d_n^T \Gamma_{k,n} \xi_n = 0}{\Gamma_{DL,k,n}^{\text{low}}} \right),
$$

s.t. (15a) - (15e), (15g) - (15j), (38), (40).

Problem $\mathbf{P}_{11}$ is still non-convex due to the non-convex constraints (15b), (15e), and (15f). For ease of handling, we rewrite the constraints (15b) and (15e) as the inequalities $\Gamma_{DL,k,n} \geq \log_2 (1 + \gamma_{DL})$ and $\Gamma_{UL,k,n} \geq \log_2 (1 + \gamma_{UL})$, respectively. Then, by substituting the left sides of the two inequalities with their corresponding lower bounds at the given points $s_{k,n}^{(l)}$ and $\tilde{d}_n^{(l)}$.
As a result, the term \( P_1(\sqrt{1 + \frac{(V_n')^2}{4V_0'}} - \frac{(V_n')^2}{2V_0'})^2 \tau \) in the constraint (15e) can be substituted by the linear component \( P_1 \vartheta n \tau \). Then, the constraint (15e) can be recast as
\[
\sum_{n=1}^{N} E_{n}^{\text{ISAC}} + \sum_{n=1}^{N} \left( P_0 \left( 1 + \frac{3(V_n')^2}{T^2_{\text{tip}}} \right) \tau + P_1 \vartheta n \tau \right) + C_0 (V_n')^3 \tau + GV_n' \tau \leq E_{\text{th}}^{\text{UAV}},
\]
which is a convex constraint.

Based on the above processing, problem \( P_{11} \) is converted into the following convex problem
\[
P_{12} : \max_{\{\vartheta_n, \sigma_n, \tau_0, \theta_n, \gamma_{k,n} \}} \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} t_{n}^{\text{DL}} \hat{g}_{k,n}^{\text{DL}}
\]
\[
+ t_{n}^{\text{UL}} 1 - n \hat{g}_{k,n}^{\text{UL}} |_{\xi_{n}=1} + t_{n}^{\text{UL}} 2 \hat{g}_{k,n}^{\text{UL}} |_{\xi_{n}=0}
\]
s.t. (15a), (15g) - (15j), (38), (40), (42) - (45),

which can be solved by CVX.

C. Joint Beamforming and UAV Trajectory Optimization

The alternating optimization algorithm for the UAV-empowered AISAC system is detailed in Algorithm 4, which alternately optimizes the beamforming and the UAV trajectory in an iterative manner until the objective value converges or the maximum iteration number is reached.

1) Convergence Analysis: We define \( \mathcal{W}(t), \mathcal{V}(t), \mathcal{R}(t), \) and \( \mathcal{S}(t) \) as the \( t \)-th iteration solution of the formulated optimization problem. The objective function is defined as \( f_o (\mathcal{W}(t), \mathcal{V}(t), \mathcal{R}(t), \mathcal{S}(t)) \). In the step 3 of Algorithm 4, \( \mathcal{W}^{(t+1)} \) can be obtained for given \( \mathcal{V}(t), \mathcal{R}(t), \) and \( \mathcal{S}(t) \). Thus, we have
\[
f_o \left( \mathcal{W}^{(t+1)}, \mathcal{V}(t), \mathcal{R}(t), \mathcal{S}(t) \right) \geq f_o \left( \mathcal{W}^{(t)}, \mathcal{V}(t), \mathcal{R}(t), \mathcal{S}(t) \right).
\]

Similarly, from the step 4–6 of Algorithm 4, we can obtain
\[
f_o \left( \mathcal{W}^{(t+1)}, \mathcal{V}^{(t+1)}, \mathcal{R}(t), \mathcal{S}(t) \right) \geq f_o \left( \mathcal{W}^{(t+1)}, \mathcal{V}(t), \mathcal{R}(t), \mathcal{S}(t) \right),
\]
\[
f_o \left( \mathcal{W}^{(t+1)}, \mathcal{V}^{(t+1)}, \mathcal{R}^{(t+1)}, \mathcal{S}(t) \right) \geq f_o \left( \mathcal{W}^{(t+1)}, \mathcal{V}(t), \mathcal{R}^{(t+1)}, \mathcal{S}(t) \right),
\]
\[
f_o \left( \mathcal{W}^{(t+1)}, \mathcal{V}^{(t+1)}, \mathcal{R}^{(t+1)}, \mathcal{S}^{(t+1)} \right) \geq f_o \left( \mathcal{W}^{(t+1)}, \mathcal{V}(t), \mathcal{R}^{(t+1)}, \mathcal{S}^{(t+1)} \right).
\]

Based on the above analysis, we have
\[
f_o \left( \mathcal{W}^{(t+1)}, \mathcal{V}^{(t+1)}, \mathcal{R}^{(t+1)}, \mathcal{S}^{(t+1)} \right) \geq f_o \left( \mathcal{W}^{(t)}, \mathcal{V}(t), \mathcal{R}(t), \mathcal{S}(t) \right),
\]
problems is method [29], [34]. The complexity of four subproblems
we solve all subproblems with the interior point
guaranteed to converge.

Non-decreasing over iterations. In addition, the throughput
which shows that the value of the objective function is
non-decreasing over iterations. Thus Algorithm 4 is
guaranteed to converge.

2) Computational Complexity Analysis: In Algorithm 4,
we solve all subproblems with the interior point
method [29], [34]. The complexity of four subproblems is $O(\log(1/\epsilon)(NKQ^2)^{3.5})$, $O(\log(1/\epsilon)(NJQ^2)^{3.5})$,
$O(\log(1/\epsilon)(NJQ^2)^{3.5})$, and $O(\log(1/\epsilon)(3N)^{3.5})$, respectively, where $\epsilon$ represents the stopping tolerance. Consequently, the complexity of Algorithm 4 in the worst case is $O(I_0 \log(1/\epsilon)(2(NKQ^2)^{3.5} + (NJQ^2)^{3.5} + (3N)^{3.5}))$, where $I_0$ denotes the iteration number.

IV. SIMULATION RESULTS

We consider a UAV-empowered AISAC system, where 4 single-antenna UEs and 2 sensing targets are randomly distributed within the 500 m $\times$ 500 m ground area. The 6-antenna UAV with the 20 kilojoules energy budget provides communication services and senses on demand within an ISAC service period. Unless otherwise stated, we consider two extreme cases in this simulation: No sensing and only communication in each time slot (i.e., $\psi = \{\psi_{\text{SN}}, \forall n\} = 0$) and ISAC in each time slot (i.e., $\psi = \{\psi_{\text{SN}}, \forall n\} = 1$). The initial and final horizontal locations of the UAV are set to (100,100,200) and (400,400,200), respectively. Unless otherwise stated, the remaining system parameters are summarized in Table I.

| Parameters                  | Value | Parameters                  | Value | Parameters                  | Value |
|-----------------------------|-------|-----------------------------|-------|-----------------------------|-------|
| Task period $T$             | 25 s  | Time slots $N$              | 25    | Channel power gain $\beta_0$| -50 dBm |
| Peak power $p_k$            | 25 dBm| Peak power $P_{\text{max}}$ | 57 dBm| Noise power $\sigma_{\text{NL},1}^2$ | -110 dBm |
| Sensing requirement $\gamma_{\text{SN}}$ | -3 dB | LoS parameter $D_{\text{SN}}$ | 0.6   | LoS parameter $\kappa$     | 0.2   |
| Maximum speed $V_{\text{max}}$ | 5 m/s | Minimum altitude $\gamma_{\text{min}}$ | 150 m | Maximum altitude $h_{\text{max}}$ | 200 m |
| Aerodynamics parameter $\rho_S$ | 80 W | Aerodynamics parameter $\rho_C$ | 31.43 W | Aerodynamics parameter $V_{\text{up}}$ | 120 m/s |
| Aerodynamics parameter $V_0$ | 4 m/s | Aerodynamics parameter $C_D$ | 0.0045 kg/m | UAV mass $m_{\text{UAV}}$ | 10 Newton |

which shows that the value of the objective function is
non-decreasing over iterations. In addition, the throughput is bounded due to the limited power. Thus Algorithm 4 is
guaranteed to converge.

In Fig. 3, we illustrate the 3D and 2D (x-y plane) UAV trajectories generated by different schemes: 1) optimized trajectory generated by Algorithm 4 (OptT1); 2) optimized trajectory generated by Algorithm 4 without the UAV energy limit (OptT2); 3) fixed straight trajectory (FixST). In the FixST
scheme, the UAV flies straightly from the initial location to
the final location. In both OptT1 and OptT2 schemes, the
UAV first flies with the maximum vertical flying speed from
the initial altitude to the minimum altitude, then keeps at the
minimum altitude as long as possible, and finally flies to the
final altitude with the maximum vertical flying speed. When
the period is large, such as $T = 35$ s, the UAV has a large
flying range and has more freedom to fly near the ground users
to obtain better channel quality for maximizing the average
system throughput. In contrast, when the period is small, such as
$T = 25$ s, the UAV flies in a small range, thus is far away
from the ground users. It also can be seen that, for the same
period $T$, the UAV flying range of the OptT1 scheme is smaller
than that of the OptT2 scheme, which indicates that the UAV
energy limit has a significant impact on the UAV trajectory.
Furthermore, we can see that, for the same period $T$, when the
UAV only performs communication (i.e., $\psi = 0$), it has more
freedom to adjust its trajectory for maximizing the average
system throughput, thus the flying range of the UAV in both
OptT1 and OptT2 schemes is relatively large. When the UAV
performs ISAC (i.e., $\psi = 1$), the QoS requirements of sensing
limit the flying range of the UAV.

B. Trajectory Comparisons of Different Schemes

In Fig. 3, we illustrate the 3D and 2D (x-y plane) UAV trajectories generated by different schemes: 1) optimized
trajectory generated by Algorithm 4 (OptT1); 2) optimized
trajectory generated by Algorithm 4 without the UAV energy
limit (OptT2); 3) fixed straight trajectory (FixST). In the FixST

C. Performance Comparisons Under Different Period, Target Speed, UAV Altitude, and Maximum UAV Flying Speed Settings

Fig. 4 shows the average system throughput under different period, target speed, UAV flying speed, and UAV altitude
settings. From Fig. 4(a), it is observed that the average system
throughput increases sharply as the period $T$ increases. This is
due to the fact that a large period $T$ offers more time resources

and degree of freedom for the UAV to adjust its trajectory for maximizing the average system throughput. In Fig. 4(b), we investigate the average system throughput when the targets are moving towards the positive direction of the $x$–axis at different speeds and far away from the ground users. It can be seen that the average system throughput decreases with the increase of the target speed. This is because when the target speed increases, the distance between the UAV and targets becomes large, and in such a case, the UAV needs to be away from the ground users and consume more resources to meet the sensing quality requirements, resulting in reducing the average system throughput. From Fig. 4(c), we can see
that as the UAV flying altitude increases, the average system throughput decreases. This is because when the altitude of the UAV is raised from 200 m to 260 m, the elevation angle of the ground users will be increased, but at the same time, the UAV will be further away from the ground users, which means more severe path loss and worse channel quality. Thus, the average system throughput is reduced. In Fig. 4(d), the average system throughput decreases with the increase of the maximum horizontal and vertical flying speeds of the UAV for \( T = 25 \) s, which is due to the fact that the mobility of the UAV is affected by the maximum flying speed. Specifically, a larger maximum flying speed allows the UAV to reach the optimal locations (the locations that can maximize the average system throughput) faster, thus increasing the average system throughput.

In Fig. 4, both the OptT1 and OptT2 schemes achieve higher average system throughput compared to the FixST scheme, which demonstrates that the UAV trajectory optimization plays a very important role in improving the average system throughput. The OptT2 scheme can achieve higher average system throughput compared to the OptT1, since the UAV has more degrees of freedom to adjust its trajectory for maximizing the average system throughput when there is no limit for the UAV energy. In addition, we can also observe that the average system throughput of the pure communication (i.e., \( \psi = 0 \)) is higher than that of ISAC (i.e., \( \psi = 1 \)). This is intuitive since sensing consumes the radio resources that can be used for communication and interferes with communication as well as restricts the freedom of the UAV trajectory adjustment.

D. Performance Comparisons of Different Sensing Policies

For some practical applications, such as the low-speed target detection or low-precision target tracking, it may be unnecessary to perform sensing all the time. Therefore, sensing should be performed adaptively according to the practical sensing requirements to avoid a waste of resources. Fig. 5 illustrates the average system throughput under different sensing policies. Policy 1: No sensing; Policy 2: The sensing interval is variable, which is configured by the proposed AISAC mechanism; Policy 3: The sensing interval is set to fixed two time slots; Policy 4: The sensing interval is set to fixed one time slot. In Policy 2, the sequential sensing intervals within the period \( T \) are set to 1, 2, 4, 8, 8, ..., 8 (time slots).

In Fig. 5, the OptT2 scheme always has the highest performance under different policies compared with the other two schemes. It is observed that the Policy 1 has the highest average system throughput. This is because communication alone occupies available radio resources and does not suffer interference from the sensing signals. In contrast, the average system throughput of the Policy 4 is the lowest. In the Policy 4, sensing will compete with communication for the limited radio resources and interfere with communication, as well as restrict the UAV trajectory adjustment, thus resulting in a sharp decrease in the average system throughput. Compared with the Policy 3, the Policy 2 can significantly improve the average system throughput by allowing high flexibility in the sensing interval configuration. By comparison, it can be seen that the larger the sensing interval, the higher the average system throughput. Besides, from the Policy 1 to the Policy 4, the sensing duration increases gradually. The longer sensing duration means consuming more radio resources and also introduces long-term interference to the communication, thus resulting in a considerable decrease in the average system throughput. The above results and analysis demonstrate that the proposed AISAC mechanism can prominently improve the average system throughput by flexibly configuring the sensing interval.

E. Performance Comparisons of Different Antenna Numbers

In the following, we compare the average system throughput of different optimization schemes under different antenna numbers. Compared with the OptT1 scheme, in the OptT1-equal power scheme, the equal power allocation instead of the optimized power is adopted. Similar definitions are for the OptT2-equal power and FixST-equal power schemes. In the OptT1-random beamforming scheme, the random beamforming is adopted instead of the optimized beamforming. The OptT2-random beamforming and FixST-random beamforming schemes have the similar definitions to the OptT1-random beamforming scheme. In both Fig. 6(a) and 6(b), the OptT1-equal power significantly outperforms the OptT1-random beamforming. Similar performance characteristics also appear between the OptT2-equal power and OptT2-random beamforming schemes, and between the FixST-equal power and FixST-random beamforming schemes. The reason is that more antennas with the beamforming optimization can offer higher beamforming gain. The effects of the power optimization are also studied in Fig. 6(a) and 6(b). The average system throughput achieved by the OptT1, OptT2, and FixST schemes is higher than that achieved by the OptT1-equal power, OptT2-equal power, and FixST-equal power schemes, respectively, which indicates that the power optimization plays an important role in improving the average system throughput. In addition, one can also find that for any scheme, the average system throughput when \( \psi = 0 \) is always higher than that when \( \psi = 1 \), which is consistent with the conclusion in the previous subsections.
In this work, we investigated the system design and performance optimization for the UAV-empowered ISAC system. First, we proposed a novel AISAC mechanism, in which the sensing duration can be flexibly configured according to the specific sensing requirements instead of maintaining a fixed configuration. Then, a joint beamforming and UAV trajectory optimization problem was formulated to maximize the average system throughput, subject to the QoS requirements of communication and sensing, UAV energy limit, UAV transmit power budget, and UAV location constraints. Furthermore, we proposed an effective alternating optimization algorithm for the formulated problem. Numerical results showed that our proposed designs significantly outperform other benchmark schemes and also confirmed the superiority of the proposed AISAC mechanism. In future works, we will extend our designs to other scenarios, e.g., multi-UAV ISAC scenarios, and achieve real-time sensing duration configuration and resource allocation, e.g., using artificial intelligence-based approaches.

V. CONCLUSION

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