A Double-Covertness Design for Integrated Sensing and Communication Systems

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Abstract—In this work, a novel double-covertness framework is developed for integrated sensing and communication (ISAC) systems, where both the radar and communication signals are protected from being maliciously detected by adversaries. Specifically, a new measurement named joint intercept probability (JIP) is proposed for characterizing the double-covertness performance. Next, an optimal power allocation strategy is designed to minimize the JIP, subject to certain quality-of-service (QoS) requirements for communication and sensing. Simulation results verify the effectiveness of our proposed solution and demonstrate the intrinsic relationship among power allocation, JIP and different QoS requirements.

Index Terms—ISAC, double-covertness, covert sensing, covert communications.

I. INTRODUCTION

Integrated sensing and communication (ISAC), which integrates the radar sensing and wireless communication to share the spectrum and hardware infrastructure, has recently emerged as a new engine for the sixth-generation (6G) wireless networks [1]. With ISAC, not only the sensing-related applications including high-resolution positioning will be strongly supported, but also a more accurate channel state information (CSI) will be estimated and predicted for communication. However, due to the broadcast nature of wireless medium and the shared usage of spectrum, ISAC systems face to a series of security threats [2], [3]. For example, for the dual-functional ISAC transmitter, the transmissions for both radar and communication signals are susceptible to be detected by the malicious adversary, which may facilitate another dangerous attacks.

To avoid the radar signals being identified and intercepted by malicious reconnaissance adversary, a covert sensing design is necessary for radar system to establish low probability of intercept (LPI) [4]. For example, in [5], the signal transmit power and the modulation schemes were jointly optimized

to mitigate power-based interceptions for LPI radar system, aided by reinforcement learning. In [6], to minimize the intercept probability, a radio frequency (RF) stealth strategy was proposed for frequency diverse array radar, in the presence of a cooperative jammer. Moreover, to enhance the LPI performance, a power allocation strategy was designed for target localization in distributed hybrid non-coherent active-passive radar networks [7].

On the other hand, from the view point of communication, guaranteeing the covertness of the communication signals from being detected by malicious warden is one of the crucial steps for security protection [8]–[10]. In [9], an energy-efficient covert communication design was proposed in an unmanned aerial vehicle (UAV) system, by exploiting the noise uncertainty to hide the presence of communication signals. More recently, in [10], a covert communication design was introduced for ISAC system, where the radar aims to send information to legitimate devices covertly against warden's surveillance by satisfying radar detection constraints. Although above works have investigated the covertness performance from the view point of radar [5]–[7] and communication [8]–[10] independently, the double-covertness design, which jointly addresses the detection and identification performance on both the radar and communication signals, is still in its vacancy stage, thus strongly motivating this work.

To fill this gap, in this work, we establish a novel double-covertness framework in ISAC systems to protect both the radar and communication signals from being detected by malicious adversaries, while guaranteeing the quality-of-service (QoS) of communication as well as sensing simultaneously. The main contributions are summarized as follows.

- A novel double-covertness framework is developed for ISAC systems and a new metric called joint intercept probability (JIP) is proposed for characterizing the double-covertness performance, by considering the probability of intercepting for both the radar and communication signals.
- To enhance the double-covertness performance, an efficient optimal power allocation strategy is designed to minimize the JIP, subject to certain QoS and reliability constraints.
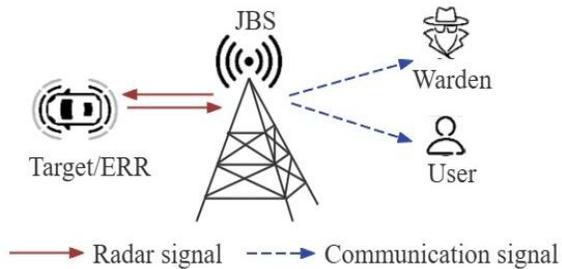- Simulation results are provided to demonstrate the ef-

Fig. 1. A double-covertness framework for ISAC systems.

fectiveness of our proposed solution and highlight the trade-off among power allocation, JIP and different QoS requirements.

The rest of this work is organized as follows. In Section II, a novel double-covertness framework is proposed and a secrecy maximization problem is formulated. Section III designs power allocation strategy to achieve double-covertness. Simulation results are given in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

As depicted in Fig. 1, a dual-functional joint base station (JBS), which is capable of providing both the communication and sensing services, transmits communication and radar signals to the ground user and target, respectively. We consider that the target, which reflects the radar signal to the JBS, also works as an electronic reconnaissance receiver (ERR) to intercept the existence of radar signal [6]. Moreover, a malicious warden, who attempts to detect the communication behavior of the JBS, launches the malicious detection attack at the same time.

A. Communication Model

We denote the horizontal locations of JBS, user, target/ERR and warden as $\boldsymbol{r}_b = (x_b, y_b)^T$, $\boldsymbol{r}_u = (x_u, y_u)^T$, $\boldsymbol{r}_e = (x_e, y_e)^T$ and $\boldsymbol{r}_w = (x_w, y_w)^T$, respectively. Denote p_c and p_r as the transmit powers for sending communication and radar signals at the JBS, respectively. By doing so, the received signal at the user is given by

$$y_u = \sqrt{p_c g_u} s_c + \sqrt{p_r g_u} s_r + z_u, \quad (1)$$

where z_u is the noise scalar with $z_u \sim \mathcal{N}(0, \sigma_u^2)$, s_c and s_r denote the communication and sensing signals, respectively, with $\mathbb{E}[|s_c|^2] = 1$ and $\mathbb{E}[|s_r|^2] = 1$. Moreover, due to the reflection and scattering effect, the communication channel between JBS and user is assumed to be Rayleigh channel. Specifically, we let $g_u = d_u^{-\alpha} h_u$, where $d_u^{-\alpha}$ represents the large-scale path loss with $d_u = \sqrt{(x_b - x_u)^2 + (y_b - y_u)^2}$ being the corresponding distance and α being the path loss factor. In addition, h_u is the small-scale fading component, which follows exponential distribution with unit mean.

As such, the signal-to-interference-plus-noise ratio (SINR) at the user is given by

$$\gamma_u = \frac{p_c d_u^{-\alpha} h_u}{p_r d_u^{-\alpha} h_u + \sigma_u^2}. \quad (2)$$

To measure the communication quality, communication outage probability (COP), which depicts the probability that the user's SINR is no greater than a preset threshold γ_0 [12], is adopted and can be given as

$$P_{OUT} = Pr(\gamma_u \leq \gamma_0) = Pr\left(h_u \leq \frac{\gamma_0 \sigma_u^2}{d_u^{-\alpha}(p_c - \gamma_0 p_r)}\right)$$
$$= \begin{cases} 1 - \exp\left(-\frac{\gamma_0 \sigma_u^2}{(p_c - \gamma_0 p_r)d_u^{-\alpha}}\right), & p_c \geq \gamma_0 p_r \\ 1, & p_c \leq \gamma_0 p_r. \end{cases} \quad (3)$$

where $Pr(\cdot)$ represents the occurrence probability of the event. In this work, we focus on the case when $p_c \geq \gamma_0 p_r$.

B. Sensing Model

Note that the radar signal will be reflected back to the JBS through the target/ERR. Since both the communication and radar signals are sent from the JBS, after decoding the communication signal, it can thus be perfectly removed from the received signal at the JBS by adopting successive cancellation method [13]. As such, the radar signal-to-noise ratio (SNR) at the JBS is given by

$$\gamma_{rad} = \frac{p_r G_B^2 \lambda^2 \rho G_P}{(4\pi)^3 k T_0 B F(d_e)^4}, \quad (4)$$

where G_B and G_P are the antenna gain and processing gain at the JBS, respectively. Moreover, ρ represents the radar cross section of the target, λ is the transmitted wavelength, k is the Boltzmann constant, T_0 is the effective noise temperature with respect to thermodynamic temperature, B represents the bandwidth of the matched filter and F depicts the radar noise factor at the JBS. In addition, d_e denotes the distance between JBS and target/ERR, i.e., $d_e = \sqrt{(x_b - x_e)^2 + (y_b - y_e)^2}$.

C. Covert Sensing Measurement: Radar Intercept Probability (RIP)

From conservation perspective, the radar signal should be hidden to avoid being identified and intercepted by the ERR, which is equipped on the target. Considering that not only the radar signal but also the communication signal as well as the environmental noise are received at the ERR, thus, the corresponding RIP is given by [6]

$$P_{RIP} = \frac{T_{OT}}{2T_I}\text{erfc}\left(\sqrt{-\ln P_{RFA}} - \sqrt{\frac{p_{r,r}}{N_0 + p_{r,c}} + 0.5}\right). \quad (5)$$

In Eq. (5), T_{OT} is the dwell time, T_I is the scan time of the ERR, and

$$\text{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-y^2} dy, \quad (6)$$

is the error function complement.

Moreover, P_{RFA} is the radar false alarm probability (RFA), $N_0 = k T_0 B_E F_E$ indicates the noise power at the ERR

with B_E and F_E being the operating bandwidth and radar noise factor at the ERR, respectively. In addition, $p_{r,r}$ and $p_{r,c}$ represent the received powers at the ERR for radar and communication signals, respectively, and can be expressed as

$$p_{r,r} = \frac{p_r G_B G_E \lambda^2}{(4\pi)^2 (d_e)^2 L_E}, \tag{7}$$

and

$$p_{r,c} = \frac{p_c G_B G_E \lambda^2}{(4\pi)^2 (d_e)^2 L_E}, \tag{8}$$

where G_E and L_E are the antenna gain and system loss coefficient at the ERR, respectively.

D. Covert Communication Measurement: Communication Intercept Probability (CIP)

Due to the existence of malicious warden, the communication behavior of the JBS might be observed and detected, where a binary hypothesis test based on the detected power is organized at the malicious warden as follows

$$p = \begin{cases} p_r d_w^{-\alpha} h_w + \sigma_w^2, & H_0 \\ (p_c + p_r) d_w^{-\alpha} h_w + \sigma_w^2, & H_1, \end{cases} \tag{9}$$

where d_w is the distance from the JBS to the warden, i.e., $d_w = \sqrt{(x_b - x_w)^2 + (y_b - y_w)^2}$, and σ_w^2 is the noise power at the warden. Moreover, h_w is the small-scale fading component of the JBS-warden link, which follows exponential distribution with unit mean. The null hypothesis H_0 indicates that only the radar signal is transmitted at the JBS. While the alternative hypothesis H_1 implies that both the communication and radar signals are transmitted at the JBS. Then, the detected power p will be compared with the detection threshold τ, i.e.,

$$p \underset{D_0}{\overset{D_1}{\gtrless}} \tau, \tag{10}$$

where D_0 and D_1 are the decisions in favor of H_0 and H_1, respectively.

To evaluate the accuracy of warden's detection, communication false alarm probability (CFA), which describes the probability that the malicious warden detects the presence of communication signal when H_0 occurs, is discussed and can be given as

$$P_{CFA} = P_r(D_1|H_0) = P_r(p_r d_w^{-\alpha} h_w + \sigma_w^2 \geq \tau)$$
$$= \begin{cases} \exp\left(-\frac{\tau - \sigma_w^2}{p_r d_w^{-\alpha}}\right), & \tau \geq \sigma_w^2 \\ 1, & \tau \leq \sigma_w^2. \end{cases} \tag{11}$$

Thus, for a given CFA, the expression of detection threshold can be expressed as

$$\tau = p_r d_w^{-\alpha} \ln\left(\frac{1}{P_{CFA}}\right) + \sigma_w^2. \tag{12}$$

Next, for any fixed CFA, P_{CFA}, we investigate the CIP, which depicts the probability that the communication signal

is detected by the warden when H_1 occurs, and is given by

$$P_{CIP} = P_r\left((p_c + p_r) d_w^{-\alpha} h_w + \sigma_w^2 \geq \tau\right)$$
$$= \exp\left(-\frac{\tau - \sigma_w^2}{(p_c + p_r) d_w^{-\alpha}}\right) = (P_{CFA})^{\frac{p_r}{p_c + p_r}}. \tag{13}$$

E. Double-Covertness Measurement

In this subsection, a novel double-covertness measurement is proposed. On the one hand, a lower RIP is expected from covert sensing perspective to avoid the radar signal being detected and intercepted by the ERR. On the other hand, from covert communication side, the smaller the P_{CIP}, the lower the probability that the communication signal will be detected by the warden.

Based on above two measurements, by setting a weighting factor w to highlight the importance and priority of guaranteeing covert sensing and covert communication, respectively, a new evaluation metric named joint intercept probability (JIP), is defined to measure the double-covertness performance and can be expressed as

$$P_{JIP} = wP_{CIP} + (1-w)P_{RIP}$$
$$= w(P_{CFA})^{\frac{p_r}{p_c + p_r}} + \frac{(1-w)T_{OT}}{2T_I}\text{erfc}\left(\sqrt{-\ln P_{RFA}}\right.$$
$$\left. - \sqrt{\frac{p_r G_B G_E \lambda^2}{N_0 (4\pi)^2 (d_e)^2 L_E + p_c G_B G_E \lambda^2} + 0.5}\right). \tag{14}$$

Note that the proposed JIP includes the probabilities for intercepting both the communication and radar signals and its range is within $[0, 1]$.

F. Problem Formulation

To enhance double covertness performance, in this work, our objective is to minimize JIP subject to given communication and sensing constraints, that is, COP and radar SNR, by optimizing the power allocation at the JBS. Thus, the optimization problem can be formulated as

$$\underset{p_c, p_r}{\text{minimize}} \quad P_{JIP} \tag{15a}$$

$$\text{s.t.} \quad 1 - \exp\left(-\frac{\gamma_0 \sigma_u^2}{(p_c - \gamma_0 p_r) d_u^{-\alpha}}\right) \leq \nu \tag{15b}$$

$$\frac{p_r G_B^2 \lambda^2 \rho G_P}{(4\pi)^3 k T_0 B F (d_e)^4} \geq \kappa \tag{15c}$$

$$p_c + p_r \leq p_{max}, \tag{15d}$$

where ν and κ are the requirements for the COP and radar SNR, respectively. Moreover, the total transmit power at the JBS should bounded by a maximum budget p_{max}.

III. PROPOSED SOLUTION

In this section, the power allocation strategy is investigated. To solve Problem (15), the impact of power allocation on P_{CIP} and P_{RIP} is investigated. First, since $P_{CFA} \leq 1$, by

taking the first-order derivative on P_{CIP} in terms of p_c, we have

$$\frac{\partial P_{CIP}}{\partial p_c} = \frac{-p_r \ln (P_{CFA})}{(p_c + p_r)^2}(P_{CFA})^{\frac{p_r}{p_c+p_r}} \geq 0, \quad (16)$$

and

$$\frac{\partial P_{CIP}}{\partial p_r} = \frac{p_c \ln (P_{CFA})}{(p_c + p_r)^2}(P_{CFA})^{\frac{p_r}{p_c+p_r}} \leq 0. \quad (17)$$

Thus, we see that P_{CIP} increases with increasing p_c and decreasing p_r. Next, for P_{RIP}, since erfc(x) is a monotonic decreasing function with respect to x, it can be observed that a lower P_{RIP} will be achieved with a smaller p_r and a larger p_c. According to above discussions, since P_{JIP} is a weighted summation between P_{CIP} and P_{RIP}, it can be seen that the monotonicity of P_{JIP} in terms of p_c and p_r is challenging to analyze for arbitrary $w \in (0, 1)$. In this case, two dimensional exhaustive search method is employed to find the optimal transmit power of p_c and p_r.

To reduce the computational complexity, we examine the feasibility of Problem (15) as follows. Under the constraint of radar SNR, the lower bound of radar power is set to satisfy (15c) with equality, i.e.,

$$p_r^{low} = \frac{\kappa}{c_1}, \quad (18)$$

where $c_1 = \frac{G_B^2 \lambda^2 \rho G_P}{(4\pi)^3 k T_0 BF(d_e)^4}$. Moreover, the COP constraint of (15b) can be re-expressed as

$$p_c \geq c_0 + \gamma_0 p_r, \quad (19)$$

where $c_0 = \frac{\gamma_0 \sigma_u^2}{\ln\left(\frac{1}{1-\nu}\right) d_u^{-\alpha}} > 0$. Next, by taking the relationship between p_c and p_r of (19) into constraint (15d), the upper bound of radar power is given by

$$p_r^{up} = \frac{p_{max} - c_0}{1 + \gamma_0}. \quad (20)$$

Thus, two dimensional search can be adopted within $p_r \in [p_r^{low}, p_r^{up}]$ and $p_c \in [c_0 + \gamma_0 p_r, p_{max} - p_r]$. Next, for two special cases when $w = 0$ and $w = 1$, the closed-form solutions are investigated as follows.

A. Special Case 1: Optimal Power Allocation When $w = 0$

In the case when $w = 0$, guaranteeing the covertness of radar signal plays the dominant role and the objective function reduces to P_{RIP}. Thus, the original optimization problem can be simplified as

$$\underset{p_c,p_r}{\text{minimize}} \ \frac{T_{OT}}{2T_I}\text{erfc}\left(\sqrt{-\ln P_{RFA}} - \sqrt{\frac{p_r b_2}{b_1 + p_c b_2} + 0.5}\right) \quad (21a)$$

s.t. $(15b) - (15d)$,

where $b_1 = N_0(4\pi)^2(d_e)^2 L_E$ and $b_2 = G_B G_E \lambda^2$. Owing to the monotonicity characteristics of erfc(x), we see that a lower P_{RIP} will be achieved with a smaller p_r and a larger p_c. Thus, to minimize P_{RIP}, the optimal power for sending radar signal,

p_r^*, should be at its lowest value within the feasible range by satisfying constraint (15c) with equality, and is given by

$$p_r^* = \frac{\kappa}{c_1}. \quad (22)$$

Moreover, p_c should be set at its largest value that satisfies constraints (15b) and (15d), within the feasible range $\left[c_0 + \frac{\gamma_0 \kappa}{c_1}, p_{max} - \frac{\kappa}{c_1}\right]$. Thus, the optimal p_c^* is given by

$$p_c^* = p_{max} - \frac{\kappa}{c_1}. \quad (23)$$

Note that the above optimal power allocation is feasible only if $c_0 + \frac{(1+\gamma_0)\kappa}{c_1} \leq p_{max}$ holds.

B. Special Case 2: Optimal Power Allocation When $w = 1$

In the special case when $w = 1$, ensuring the covertness of communication is with the highest priority and the objective function reduces to P_{CIP}. As such, the original optimization problem can be simplified as

$$\underset{p_c,p_r}{\text{minimize}} \ (P_{CFA})^{\frac{p_r}{p_c+p_r}} \quad (24a)$$

s.t. $(15b) - (15d)$.

According to Eqs. (16) and (17), we see that the objective function in (24a) decreases with decreasing p_c and the optimal p_c should be set at its lowest value by satisfying the COP constraint of (15b) with equality, i.e., $p_c = c_0 + \gamma_0 p_r$. Next, by taking the relationship between p_c and p_r into Problem (24), the original optimization can be further transformed as

$$\underset{p_r}{\text{minimize}} \ P_{CIP} = (P_{CFA})^{\frac{p_r}{c_0+(1+\gamma_0)p_r}} \quad (25a)$$

$$\text{s.t.} \ p_r \geq \frac{\kappa}{c_1} \ \text{and} \ p_r \leq \frac{p_{max} - c_0}{1 + \gamma_0}. \quad (25b)$$

Notice that the above optimization problem is feasible only if $\frac{\kappa}{c_1} \leq \frac{p_{max}-c_0}{1+\gamma_0}$. Moreover, by taking the first-order derivative of the objective function (25a) with respect to p_r, since $P_{CFA} \leq 1$, we have

$$\frac{\partial P_{CIP}}{\partial p_r} = \frac{c_0 \ln (P_{CFA})}{[c_0 + (1+\gamma_0)p_r]^2}(P_{CFA})^{\frac{p_r}{c_0+(1+\gamma_0)p_r}} \leq 0. \quad (26)$$

Thus, a higher p_r contributes to a lower objective value, and the optimal power allocation in this case is given by

$$p_r^* = \frac{p_{max} - c_0}{1 + \gamma_0} \ \text{and} \ p_c^* = c_0 + \frac{\gamma_0(p_{max} - c_0)}{1 + \gamma_0}. \quad (27)$$

IV. SIMULATION RESULTS

In this section, we validate the effectiveness of our proposed solution and extract design insights related to COP and radar SNR constraints. Unless stated otherwise, we apply the following simulation configurations as listed in Table I.

In Fig. 2, the optimal power allocation, JIP, instantaneous COP and radar SNR versus different values of weighting factor w are plotted when $\kappa = 10$ dB and $\nu = 0.001$. Several interesting observations can be found. According to Figs. 2(a) and 2(b), the correctness of our theoretical optimal power allocation strategy in special two cases is verified since the

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
G_B	30 dB	r_b	$(0\ m, 0\ m)^T$
α	3.5	r_u	$(80\ m, 80\ m)^T$
σ_u^2, σ_w^2	-120 dB	r_w	$(100\ m, 100\ m)^T$
γ_0	1 dB	r_e	$(1500\ m, 1500\ m)^T$
λ	0.03 m	ρ	$1\ m^2$
T_0	290 K	k	1.38×10^{-23} Joule/K
F	3 dB	F_E	10 dB
B	0.04 GHz	B_E	1 GHz
G_E	3 dB	G_P	12 dB
L	10 dB	T_{OT}	0.8 sec
P_{RFA}	10^{-4}	P_{CFA}	10^{-6}
p_{max}	25 Watt	T_I	1 sec

theoretical optimal powers (green dots) match the exhaustive search values well.

Next, the intrinsic relationship between optimal power allocation, JIP, instantaneous COP and radar is discussed. We see that when $w = 0$ and JIP reduces to P_{RIP}, the optimal radar power is at its least value to satisfy the radar SNR requirement with equality, thus, the instantaneous radar SNR as shown in Fig. 2(e) is exactly the same as κ, i.e., 10 dB. Moreover, when $w = 0$, the optimal communication power is set at its largest value, i.e., $p_c^* = p_{max} - p_r^*$, since the P_{RIP} decreases with increasing p_c. Under this settings, as the communication power is large, the probability that the communication outages is very low, approximately equals to 0 as shown in Fig. 2(d).

Then, according to Figs. 2(a) and 2(b), with an increased weighting factor w, we see that the optimal radar power p_r^* keeps unchanged while the optimal communication power p_c^* first decreases then keeps unchanged when $w \in [0, 0.83]$. Correspondingly, it can be observed from Fig. 2(e) that the instantaneous radar SNR is kept at 10 dB when $w \in [0, 0.83]$ since p_r^* is not changed. Moreover, when p_c^* drops to 11.347 Watt, the lower bound of p_c to exactly meet the COP constraint with equality at $w = 0.36$, we can find that the instantaneous COP is the same as ν, i.e., 10^{-3}. In addition, as shown in Fig. 2(c), we notice that the JIP first increases and then decreases with increasing w, this trend is affected by all system configurations related to P_{RIP} and P_{CIP} as shown in Table I.

Moreover, when $w = 1$ and JIP reduces to P_{CIP}, we see that the optimal communication and radar powers are set to satisfy the COP and maximum power budget constraints with equality jointly, since P_{CIP} decreases with decreasing p_c and increasing p_r. Thus, we can see from Figs. 2(a), 2(b) and 2(d) that the COP is exactly equals to 10^{-3} and $p_c^* + p_r^* = p_{max} = 25$ Watt. Additionally, as p_r^* is at its upper bound, a higher radar SNR can be achieved as shown in Fig. 2(e).

In Fig. 3, the relationship between JIP and radar SNR requirements κ is plotted with different COP constraints ν when $w = 0.5$. First, it can be observed that a more strict radar SNR requirement results in a higher value of JIP. Specifically, when $\nu = 0.003$, the JIP increases from $2.477 * 10^{-3}$ to
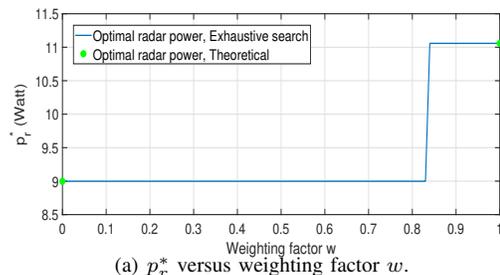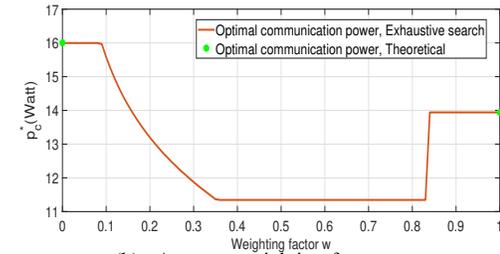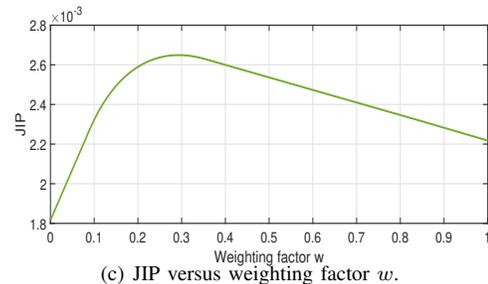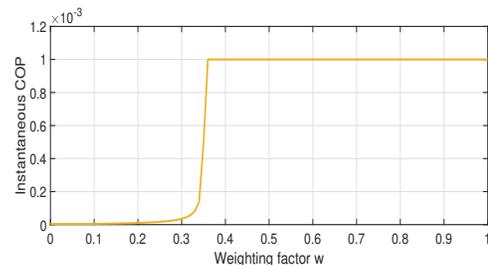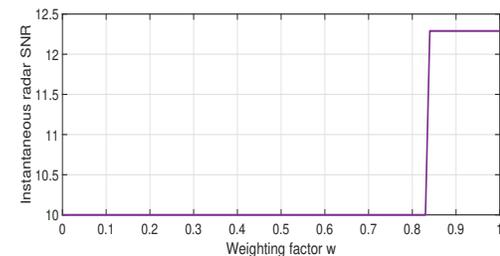

(a) p_r^* versus weighting factor w.

(b) p_c^* versus weighting factor w.

(c) JIP versus weighting factor w.

(d) Instantaneous COP versus weighting factor w.

(e) Instantaneousradar SNR versus weighting factor w.

Fig. 2. Optimal power allocation, JIP, instantaneous COP and radar SNR versus different values of weighting factor when $\kappa = 10$ dB and $\nu = 0.001$.

$2.529 * 10^{-3}$ when κ jumps from 5 dB to 10 dB. Moreover, it can be seen that with a more strict COP constraint, i.e., a lower value of ν, a higher JIP will be obtained. In specific, when $\kappa = 5$ dB, the JIP decreases from $2.483 * 10^{-3}$ to $2.477 * 10^{-3}$ when ν increases from 0.001 to 0.003.
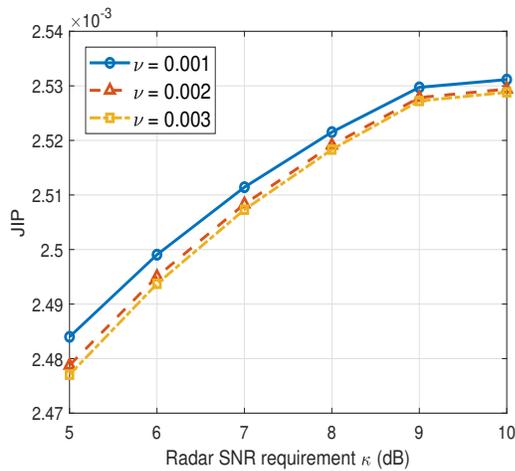
Fig. 3. JIP versus radar SNR requirements with different COP constraints ν when $w = 0.5$.

V. CONCLUSION

In this work, a novel double-covertness framework was developed for ISAC systems. Specifically, to evaluate the double-covertness performance, a new metric of JIP was proposed by considering the probability of intercepting both the radar and communication signals. Next, aimed to minimize the JIP, optimal power allocation scheme was designed by satisfying communication and sensing QoS constraints. Finally, simulation results verified our theoretical analysis on the relationship between power allocation, JIP as well as communication and radar QoS performance.

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