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Low Probability of Intercept-Based Optimal OFDM Waveform Design Strategy for an Integrated Radar and Communications System

CHENGUANG SHI[1,2], FEI WANG[1], SANA SALOUS[3], (Senior Member, IEEE), AND JIANJIANG ZHOU[1], (Member, IEEE)

[1]Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing University Of Aeronautics and Astronautics, Nanjing 210016, China

[2]Key Laboratory of Dynamic Cognitive System of Electromagnetic Spectrum Space, Ministry of Industry and Information Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

[3]School of Engineering and Computing Sciences, Durham University, Durham DH1 3DE, U.K.

Corresponding author: Fei Wang (wangxiaoxian@nuaa.edu.cn).

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ABSTRACT The integration of radar and communications systems can provide great advantages, such as enhanced efficiency, structure simplification, less occupied hardware resources, and interference mitigation, compared with traditional individual radar and communications applications. Extensive studies have presented achieving improved system performance, whereas the problem of low probability of intercept (LPI)-based waveform design for the integrated system is seldom discussed in the literature. In this paper, an LPI-based optimal orthogonal frequency multiplexing modulation (OFDM) waveform design strategy is developed for an integrated radar and communications system (IRCS). The dedicated transmitter in this system transmits integrated OFDM waveform for simultaneously target parameter estimation and downlink communications. The basis of the underlying strategy is to employ the optimization technique to design the integrated OFDM waveform of IRCS in order to minimize the total radiated power, while satisfying the specified requirements of target parameter estimation and data information rate. We analytically show that the resulting optimization problem is convex and can be solved by formulating the Karush–Kuhn–Tuckers optimality conditions. Numerical simulation results demonstrate that our proposed strategy can solve the waveform design problem in the IRCS with low complexity, and the LPI performance of the IRCS can efficiently be enhanced by utilizing the proposed integrated OFDM waveform design strategy.

INDEX TERMS Integrated radar and communications system (IRCS), low probability of intercept (LPI), conditional mutual information (MI), orthogonal frequency multiplexing modulation (OFDM), waveform design.

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

Radar sensing and wireless communications are two of the most prominent functions based on similar radio frequency (RF) phenomena, which have previously been developed as two separate entities [1]. The typical goal of a radar system is to detect, localize, and track enemy targets, whereas the goal of a communications system is to broadcast information from a source to a user and enhance its reliability [2]. However, due to the dramatical increase of the commercial wireless communications, the problem of RF spectrum congestion has received great consideration in recent years. It is reported that the number of RF devices will jump to more than 20 billion by the year of 2020 [3]. In particular, the spectrum sharing between radar and communications has been the focus of intensive studies [3]–[16]. Hence, the spectral coexistence of radar and communications is capable of not only easing competition over bandwidth, but also improving spectral efficiency of cognitive radio devices.

In [9], a novel cooperative strategy for the spectral coexistence of a multiple-input multiple-output (MIMO) communication system and a matrix completion based collocated MIMO radar is proposed. The primary objective of this work is to maximize the radar signal-to-interference-plus-noise ratio (SINR) by jointly optimizing the radar transmit precoder, the radar subsampling method, and the communication transmit covariance matrix, while satisfying specified communication rate and power resource constraints. In [10], Liu *et al.* formulate two optimization-based beamforming algorithms for MIMO radar and downlink multi-user multiple-input single-output (MU-MISO) communication coexistence, and the multi-user interference is employed to improve the communication performance and relax the constraints in the resulting problems. Furthermore, the problem of waveform design is also known as the research hotpot in spectrum sharing. Since the orthogonal frequency division multiplexing (OFDM) waveform is one of the best candidates for both radar sensing and communications applications, Bica *et al.* present several OFDM-based radar waveform design algorithms in spectral sharing environments [11]–[13]. As an extension, Shi *et al.* [14] develop the power minimization-based robust OFDM radar waveform design for radar and communication systems in coexistence. Three different waveform design criteria are proposed to minimize the worst-case power consumption of radar by optimizing the transmitted OFDM radar waveforms, which are constrained by a desired mutual information (MI) requirement for target characterization and a minimum channel capacity for communication transferring. The above criteria differ in the way the communication signals scattered off the target are considered as useful energy, as interference, or ignored altogether. Moreover, reference [15] addresses the problem of spectrally compatible waveform design for MIMO radar in the presence of multiple targets and signal-dependent interference, which minimizes the waveform energy of the overlayed space-frequency bands under constraints of waveform similarity and individual SINR requirements. It is also shown that the proposed method can offer good robustness against large interference uncertainties. Qian *et al.* [16] investigate the joint design of the transmit waveform for MIMO radar system and the transmit covariance matrix for MIMO wireless communication system.

Although the above research provides us a guidance to tackle with the problem of spectral coexistence of radar and communications, it should be pointed out that for supporting spectrum sharing, radar and wireless communications devices are essentially required to exchange side-information, such as channel state information, communication modulation format, radar transmitted waveforms, to achieve a beneficial cooperation [3]. In contrast to the spectrum sharing strategies, a much more favorable technique is to integrate the radar sensing and communications applications, where the above problem does not exist. The integrated radar and communications system (IRCS) can share the same hardware resources with the high similarity of transceiver structures, while the related processing is also needed in signal generation and separation. There is no doubt that the IRCS is able to provide several advantages in cost reduction, structure simplification, mitigation electromagnetic interference, etc.

B. RELATED LITERATURE REVIEW

Generally speaking, the IRCS can remarkably enhance the work efficiency of the entire system, and thus it has attracted significant interests from academic researchers. Paul *et al.* [17] give us a point of departure for future researchers that may be needed to solve the problem of spectral congestion by presenting the topologies, levels of system integration, and outlines of future systems. Later, they define the achievable inner bounds on performance of coexistence between radar and communications systems [18], [19], in which the corresponding bounds are measured in terms of radar estimation information rate for the radar and data information rate for communications. In [20], Schrrenbroich and Zatman formulate a joint radar-communications resource management framework, which integrates the radar and communications functions into a single shared-spectrum system. In [21], the radar MI and communication channel capacity of an IRCS utilizing MIMO antennas are analyzed, and the effects of signal-to-noise ratio (SNR) and the number of antennas on the MI and capacity are revealed respectively. Liu *et al.* [22] propose an IRCS with MIMO-OFDM waveform, wherein the different limitations of radar and communications in designing such a system is studied. The problem of adaptive OFDM IRCS waveform design based on information theory is investigated in [23]. Under the constraint on the total transmit power, the resulting problem is formulated to simultaneously optimize the conditional MI for radar and data information rate for communications. Besides, the multi-objective optimal waveform design for OFDM IRCS is devised in [24], and two different waveform design schemes are proposed to simultaneously enhance the estimation accuracy of range and velocity in radar and the channel capacity in communications. Huang *et al.* [25] presents a phased array radar-based channel modeling and sparse channel estimation for an IRCS. Also, to minimize the information security risk, Chalise and Amin [26] formulate a unified radar and communications system, where the SINR at the radar receiver is maximized while guaranteeing that the information secrecy rate is above a specified threshold. The transmissions of radar waveforms and information signals are scheduled with the disjoint and with the same set of resources are both considered.

Nevertheless, the vast majority of existing studies formulates various optimization strategies to enhance the system efficiency of IRCS, without paying much attention to the problem of low probability of interception. In a realistic scenario, low probability of intercept (LPI) performance optimization is a crucial part of military operations in hostile environments [27]–[32]. In such a case, controlling transmit resources that are required to fulfill the predetermined task is a critical issue. To this end, minimizing the radiated power, enlarging revisit interval, and exploiting waveform agility could result in better LPI performance of the entire system [14]. To the best of our knowledge, although the integration of radar and communications functions is a fast emerging research field, there is no previous work regarding the problem of LPI-based optimal OFDM waveform design for an IRCS in the literature. The urgent need for LPI optimization in the integrated system should be further emphasized, which is due to the fact that more transmitted power might lead to electronic or physical attacks in modern battlefield. Therefore, in this work, we will extend the results in [14] and [23] and propose an LPI-based optimal OFDM waveform design strategy for IRCS. These aspects render this mathematical optimization model attractive for offence applications, where the loader of the system needs to achieve LPI performance.

C. MAJOR CONTRIBUTIONS

Overall speaking, this paper concentrates on how to design the optimal integrated OFDM waveform for LPI purpose. Our previous study in [14] was the first to propose the power minimization-based robust OFDM radar waveform design algorithm for radar and communication systems in coexistence. However, there were some differences and limitations in [14] that are overcome in this work. Firstly, the radar and communications systems were designed in different manners. They were not deployed from the same platform. Secondly, the radar and communication systems transmitted different OFDM signals in the same frequency band, which caused too much inter-system interference to each other. Thirdly, it did not provide a theoretical insight into the LPI performance of the system. Our current study overcomes these limitations and provides a further in-depth analysis of the IRCS. For clarity, the major contributions of this paper are the following:

1) *An LPI-based optimal OFDM waveform design strategy is developed for IRCS, and then formulated as an optimization problem.* Mathematically speaking, the integrated OFDM waveform design strategy is built to minimize an objective function about the total transmitted power of IRCS, while satisfying the predetermined requirements of target parameter estimation and data information rate. To gauge the estimation accuracy of the target impulse response, it is common to employ the well-known conditional MI [23]. For communications, the data information rate is an important performance metric. As such, the basis of this paper is to optimally design the integrated OFDM waveform, which can result in the LPI performance enhancement.
2) *We strictly demonstrate that the proposed OFDM waveform design strategy can be reformulated as a convex optimization problem.* It is assumed that the precise knowledge of the power spectral densities (PSDs) of target and colored noise is available. Then, by calculating the second derivative of the constraint function, we analytically prove that the resulting optimization problem is convex. In addition, we also show that the first derivative of the constraint is a monotonic function, which is able to simplify the later solution procedure [29].
3) *We present an efficient solution procedure based on the Karush-Kuhn-Tuckers (KKT) optimality conditions to deal with the underlying convex optimization problem.* It is introduced in [27], [33], and [34] that the KKT conditions can be applied to give a set of sufficient conditions for the optimal solution to the proposed integrated OFDM waveform design strategy due to its property of convex. By deriving the KKT conditions, the convex optimization problem can be transformed into a nonlinear equation solving problem, which can further be solved through the well-known bisection search approach.
4) *Several numerical examples are provided to demonstrate the effectiveness of the proposed LPI-based OFDM waveform design strategy.* More specifically, more transmit power is allocated to the subcarriers which have larger target PSD and suffer less noise power. Moreover, it is also illustrated that the LPI performance of the IRCS can efficiently be enhanced by exploiting the proposed integrated OFDM waveform design scheme.

D. ORGANIZATION AND NOTATION

The rest of this paper is organized as follows: Section II describes the integrated signal model. The LPI-based optimal OFDM waveform design strategy is developed for an IRCS in Section III. In Section III-A, the basis of the underlying waveform design strategy is introduced. Then, the mathematical optimization framework of the LPI-based integrated OFDM waveform design strategy is built in Section III-B. In Section III-C, the resulting convex optimization problem is solved by the KKT optimality conditions. The numerical results and discussions upon the results are provided in Section IV. Finally, the conclusions of the paper can be found in Section V.

The following notations are adopted. Throughout the paper, a denotes a scalar, $\mathbf{a}$ denotes a column vector, and $\mathbf{A}$ denotes a matrix. We denote the nth element of a vector $\mathbf{a}$ by a_n. $a(t)$ is the continuous time domain signal, and $A[n]$ is the frequency domain representation of a discrete sample. The superscripts $(\cdot)^T$ represents the transpose, and the superscript $(\cdot)^*$ indicates the optimality.

II. INTEGRATED SIGNAL MODEL

This section formulates the integrated signal model and presents system parameters used in the following. Let us consider an IRCS as illustrated through the block diagram of Figure 1. The integrated system is capable of supporting both radar and communications functions. In the scenario under consideration, the dedicated transmitter simultaneously radiates OFDM waveform to the hostile target and downlink user. In this work, we assume that the channels are stationary over the observation period. At the downlink communications user, it is also assumed that the transmitted signal scattered off the target is much weaker than that coming through the

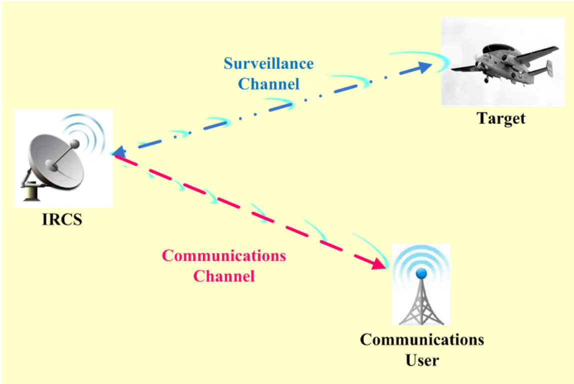

FIGURE 1. Illustration of the IRCS model.

communications channel, and can be ignored for simplicity. The aim of the IRCS here is to minimize the total radiated power of the underlying system by optimally designing the OFDM waveform, which is constrained by a predetermined MI requirement for target characterization, a specified data information rate for downlink user, and a maximum transmit power in each subcarrier.

For an IRCS, the transmitted integrated OFDM waveform $s_{\mathrm{rc}}(t)$ with M_{c} subcarriers can be expressed as [14]:

$$s_{\mathrm{rc}}(t) = \frac{1}{\sqrt{M_{\mathrm{c}}}} \sum_{n=0}^{M_{\mathrm{c}}-1} a_n e^{j2\pi(f_{\mathrm{o}}+n\Delta f)t}, \tag{1}$$

where a_n is the amplitude of the nth subcarrier of OFDM waveform, f_{o} is the carrier frequency, and Δf represents the subcarrier spacing. The matrix formulation for the discrete time version of (1) can be written as [13]:

$$\mathbf{S}_{\mathrm{rc}} = \mathbf{W}_{M_{\mathrm{c}}}\mathbf{A}, \tag{2}$$

where $\mathbf{W}_{M_{\mathrm{c}}}$ is a $M_{\mathrm{c}} \times M_{\mathrm{c}}$-dimensional inverse discrete Fourier transform (IDFT) matrix

$$\mathbf{W}_{M_{\mathrm{c}}} = \frac{1}{\sqrt{M_{\mathrm{c}}}} \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & W_{M_{\mathrm{c}}} & \cdots & W_{M_{\mathrm{c}}}^{M_{\mathrm{c}}-1} \\ 1 & W_{M_{\mathrm{c}}}^2 & \cdots & W_{M_{\mathrm{c}}}^{2(M_{\mathrm{c}}-1)} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & W_{M_{\mathrm{c}}}^{M_{\mathrm{c}}-1} & \cdots & W_{M_{\mathrm{c}}}^{(M_{\mathrm{c}}-1)(M_{\mathrm{c}}-1)} \end{bmatrix} \tag{3}$$

with $W_{M_{\mathrm{c}}} = e^{j2\pi/M_{\mathrm{c}}}$. $\mathbf{A} = [a_0, a_1, \cdots, a_{M_{\mathrm{c}}-1}]^T$ is a $M_{\mathrm{c}} \times 1$ vector that contains the weights of all subcarriers.

Then, the received signal at the receiver of IRCS can be described as:

$$\begin{aligned} r(t) &= s_{\mathrm{rc}}(t) * g(t) + v(t) \\ &= \int_{-\infty}^{\infty} g(\tau)s_{\mathrm{rc}}(t-\tau) + v(t), \end{aligned} \tag{4}$$

where $r(t)$ represents the received signal at the receiver of IRCS, $g(t)$ denotes the impulse response of an extended target, τ is the time delay of the target, and $v(t)$ is the additive colored noise with known variance.

Remark 1: It should be highlighted that the all-cell Doppler correction (ACDC) scheme is utilized to enable an inter-carrier-interference (ICI) free processing for the integrated OFDM systems. With the method proposed in [35], the cyclic prefix can be omitted. As such, it is a significantly valuable feature for both radar and communications applications.

In what follows, we formulate the LPI-based optimal OFDM waveform optimization problem that minimize the total transmitted power of IRCS subject target parameter estimation and data information rate constraints.

III. PROBLEM FORMULATION

A. BASIS OF THE TECHNIQUE

Mathematically, the LPI-based optimal OFDM waveform design strategy for an IRCS can be described as a problem of minimizing a cost function about the total radiated power, while satisfying a predefined target characterization performance and a specified data information rate. In this paper, the adaptable parameter is the integrated OFDM waveform. The conditional MI can be utilized as an appropriate metric to evaluate the estimation performance of the target impulse response, and the data information rate is adopted as an important performance metric for communications. We are then in a position to design the integrated OFDM waveform in order to achieve better LPI performance for the IRCS. The general LPI-based optimal OFDM waveform design strategy can be detailed as follows.

B. LPI-BASED INTEGRATED OFDM WAVEFORM DESIGN STRATEGY

The conditional MI enables one to evaluate the estimation accuracy of the extended target impulse response, which can be utilized as an appropriate metric for radar target characterization. Previously, the analytical expression of MI has already been derived in [23]. Thus, the conditioned MI for IRCS can be written as [14] and [23]:

$$\begin{aligned} &\mathcal{I}(r(t); g(t)|s_{\mathrm{rc}}(t)) \\ &\quad = \sum_{n=0}^{M_{\mathrm{c}}-1} \log\left(1 + \frac{|A[n]|^2|H_{\mathrm{rc}}[n]|^2L_{\mathrm{rc}}[n]}{\sigma_{\mathrm{v}}^2[n]}\right), \end{aligned} \tag{5}$$

where M_{c} is the number of sucarriers, $A[n]$ is the amplitude of the integrated waveform in the nth subcarrier in frequency domain, $|A[n]|^2$ denotes the power of the integrated waveform in the nth subcarrier, $H_{\mathrm{rc}}[n]$ denotes the target spectrum for the surveillance channel in the nth subcarrier, $\sigma_{\mathrm{v}}^2[n]$ represents the power of the colored noise in the nth subcarrier, and $L_{\mathrm{rc}}[n]$ represents the propagation loss of the surveillance channel in the nth subcarrier:

$$L_{\mathrm{rc}}[n] = \frac{G_{\mathrm{t}}G_{\mathrm{r}}\lambda_n^2}{(4\pi)^3R_{\mathrm{rc}}^4}, \tag{6}$$

where G_t is the transmitting antenna gain of the IRCS, G_{r} is the receiving antenna gain of the IRCS, λ_n is the wavelength in the nth subcarrier, and R_{rc} denotes the distance between the IRCS and the target. In this scenario, it is assumed that the exact knowledge of the PSDs of target and colored noise is available. Herein, it is noteworthy that the term $|H_r[n]|^2 L_r[n]/\sigma_v^2[n]$ in (5) can be regarded as the signal-to-noise ratio (SNR) in the nth subcarrier.

It is implied in [14] and [23] that the data information rate is an important performance metric for wireless communications. Particularly, in the frequency selective fading channel, the data information rate can be improved by optimally allocating the waveform power in each subcarrier. Hence, the data information rate in the nth subcarrier can be expressed by:

$$C_t[n] = \log\left(1 + \frac{|A[n]|^2 L_c[n]}{\sigma_v^2[n]}\right), \tag{7}$$

where $L_c[n]$ denotes the propagation loss of the communications channel:

$$L_c[n] = \frac{G_s^2 \lambda_n^2}{(4\pi)^2 R_c^2}, \tag{8}$$

where G_s is the transmitting/receiving antenna gain of the communication channel, and R_c is the distance between the IRCS and the downlink user. Similarly, the term $L_c[n]/\sigma_v^2[n]$ in (7) can be interpreted as the SNR in the nth subcarrier.

According to (5) and (7), one can notice that the target estimation accuracy and data information rate are related to many parameters. The adaptable parameter that is considered in this paper is the integrated OFDM waveform $|A[n]|^2$. For the predetermined requirements of target parameter estimation and data information rate, the aim of our paper is to optimally design the integrated OFDM waveform of the IRCS, which can result in the minimization of the total radiated power. Therefore, the resulting optimization problem can be given by:

$$(\mathbf{P0}): \min_{|A[n]|^2, n\in\mathcal{M}_n} \sum_{n=0}^{M_c-1} |A[n]|^2, \tag{9a}$$

$$\text{s.t.} \begin{cases} \sum_{n=0}^{M_c-1} \log\left(1 + \frac{|A[n]|^2 |H_{rc}[n]|^2 L_{rc}[n]}{\sigma_v^2[n]}\right) \\ \quad \geq \phi_{MI}, \\ \log\left(1 + \frac{|A[n]|^2 L_c[n]}{\sigma_v^2[n]}\right) \geq C_{min}, \\ 0 \leq |A[n]|^2 \leq P_{max,n}. \end{cases} \tag{9b}$$

where $\mathcal{M}_n \triangleq \{0, 1, \cdots, M_c - 1\}$ represents the index-set of all M_c subcarriers, ϕ_{MI} denotes the specified MI threshold for target characterization performance, C_{min} is the minimum required data information rate for the downlink communications user in the nth subcarrier, and $P_{max,n}$ is the maximum transmit power in the nth subcarrier.

In problem (**P0**), the first constraint suggests that the achieved conditional MI should be greater than a predefined MI threshold value ϕ_{MI} such that the desired target estimation performance is satisfied, while the second one stands that the data information rate in the nth subcarrier should be above the threshold value C_{min} to guarantee its communications requirement. The last constraint stands that the transmit power in the nth subcarrier is constrained by a minimum value 0 and a maximum value $P_{max,n}$.

C. SOLUTION PROCEDURE

After simplifying the second constraint in (9b), we can rewrite the above optimization problem (**P0**) as:

$$(\mathbf{P1}): \min_{|A[n]|^2, n\in\mathcal{M}_n} \sum_{n=0}^{M_c-1} |A[n]|^2, \tag{10a}$$

$$\text{s.t.} \begin{cases} \sum_{n=0}^{M_c-1} \log\left(1 + \frac{|A[n]|^2 |H_{rc}[n]|^2 L_{rc}[n]}{\sigma_v^2[n]}\right) \\ \quad \geq \phi_{MI}, \\ \frac{\sigma_v^2[n](e^{C_{min}} - 1)}{L_c[n]} \leq |A[n]|^2 \leq P_{max,n}. \end{cases} \tag{10b}$$

Let us defined the following notations

$$\begin{cases} a_n = |A[n]|^2, \\ l_n = \frac{\sigma_v^2[n]}{|A[n]|^2 |H_{rc}[n]|^2 L_{rc}[n]}, \\ m_n = \frac{\sigma_v^2[n](e^{C_{min}} - 1)}{L_c[n]}, \end{cases} \tag{11}$$

then the optimization problem (**P1**) can equivalently be reformulated as follows:

$$(\mathbf{P2}): \min a_n, n \in \mathcal{M}_n \sum_{n=0}^{M_c-1} a_n, \tag{12a}$$

$$\text{s.t.} \begin{cases} \mathbf{C1}: \sum_{n=0}^{M_c-1} \log\left(1 + \frac{a_n}{l_n}\right) \geq \phi_{MI}, \\ \mathbf{C2}: \mathbf{m} \leq \mathbf{a} \leq \mathbf{P}_{max}. \end{cases} \tag{12b}$$

where $\mathbf{a} = [a_0, \cdots, a_{M_c-1}]^T$, $\mathbf{m} = [m_0, \cdots, m_{M_c-1}]^T$, and $\mathbf{P}_{max} = [P_{max,0}, \cdots, P_{max,M_c-1}]^T$.

Before solving the resulting problem (**P2**), some necessary propositions are provided in the following.

Proposition 1: The optimization problem (**P2**) is a convex problem, with the following properties:

a) The conditional MI $\sum_{n=0}^{M_c-1} \log\left(1 + \frac{a_n}{l_n}\right)$ is a monotonic increasing function of a_n;

b) The second derivative of $\frac{\partial}{\partial a_n} \sum_{n=0}^{M_c-1} \log\left(1 + \frac{a_n}{l_n}\right)$ is monotonic decreasing in a_n.

Proof: According to the expression of the conditional MI in (5), we can obtain:

$$\frac{\partial}{\partial a_n}\left[\log\left(1 + \frac{a_n}{l_n}\right)\right] = \frac{1}{a_n + l_n} > 0, \tag{13}$$

$$\frac{\partial}{\partial a_j}\left[\log\left(1 + \frac{a_n}{l_n}\right)\right] = 0, \quad \forall n \neq j, \tag{14}$$

and

$$\frac{\partial^2}{\partial a_n^2}\left[\log\left(1 + \frac{a_n}{l_n}\right)\right] = -\frac{1}{(a_n + l_n)^2} < 0, \tag{15}$$

$$\frac{\partial^2}{\partial a_n a_j}\left[\log\left(1 + \frac{a_n}{l_n}\right)\right] = 0, \quad \forall n \neq j, \tag{16}$$

From the above derivations, it can be observed that (13) implies the increasing nature of the conditional MI with respect to a_n, and (15) suggests that the decreasing nature of the second derivative of MI with respect to a_n. Moreover, (15) and (16) indicate that the Hessian matrix of the conditional MI in (5) with respect to a_n is a diagonal matrix with non-positive elements. Thus, it is shown that the conditional MI is increasing and concave with respect to a_n.

As a consequence, the constraint **C1** constitutes a convex feasible set over a_n, while the objective function is affine and the power constraint **C2** is the intersection of $2M_c$ half-spaces, and hence convex [14], [33], [34], which completes the proof. ∎

Proposition 2: It is assumed that the precise knowledge of the PSDs of target and colored noise is available. Then, under the predetermined requirements for target parameter estimation and data information rate, the LPI-based optimal OFDM waveform corresponding to the optimization problem (**P0**) that minimizes the total radiated power of IRCS should satisfy the following equation:

$$a_n^* = \begin{cases} m_n, & l_n \geq \xi_3^* - m_n, \\ \xi_3^* - l_n, & \xi_3^* - P_{\max,n} < l_n < \xi_3^* - m_n, \\ P_{\max,n}, & l_n < \xi_3^* - P_{\max,n}, \end{cases} \tag{17}$$

where ξ_3^* is called *water-level* and can be determined by the conditional MI constraint:

$$\sum_{n=0}^{M_c-1} \log\left(1 + \frac{a_n^*}{l_n}\right) \geq \phi_{\mathrm{MI}}, \tag{18}$$

Proof: Generally speaking, a large number of global optimization techniques, such as branch and bound, gradient projection, and interior point methods, can be applied to obtain the optimum solution for the aforementioned optimization problem (**P2**). However, those global optimization approaches require exponential complexity and becomes computationally prohibitive in IRCS, where M_c can take a large value [26]. On the other hand, no analytically closed-form expression of the optimum solution can be got [14], [33], [34]. Thus, to derive the analytical closed-form solution, the technique of Lagrange multipliers is exploited to solve the optimization problem (**P2**) [36], [37], which can equivalently be given by:

$$\mathcal{L}(\mathbf{a}, \boldsymbol{\xi}_1, \boldsymbol{\xi}_2, \xi_3) = \sum_{n=0}^{M_c-1} a_n + \boldsymbol{\xi}_1^T(\mathbf{m} - \mathbf{a}) + \boldsymbol{\xi}_2^T(\mathbf{a} - \mathbf{P}_{\max}) + \xi_3\left[\phi_{\mathrm{MI}} - \sum_{n=0}^{M_c-1} \log\left(1 + \frac{a_n}{l_n}\right)\right], \tag{19}$$

where $\boldsymbol{\xi}_1 \geq \mathbf{0}$, $\boldsymbol{\xi}_2 \geq \mathbf{0}$, and $\xi_3 \geq 0$ denote the corresponding Lagrange multipliers for multiple constraints. It should be noted that because of the convex nature of (**P2**), the KKT optimality conditions are the necessary and sufficient conditions for the global optimality a_n^*, $n \in \mathcal{M}_n$, and the Lagrange multipliers $\boldsymbol{\xi}_1^*$, $\boldsymbol{\xi}_2^*$, and ξ_3^*. In order to solve the convex problem (**P2**), the KKT conditions are subsequently listed in the following:

$$\frac{\partial \mathcal{L}(\mathbf{a}, \boldsymbol{\xi}_1, \boldsymbol{\xi}_2, \xi_3)}{\partial a_n} = 1 - \xi_{1,k}^* + \xi_{2,k}^* - \frac{\xi_3^*}{a_n^* + l_k} = 0, \tag{20a}$$

$$(\boldsymbol{\xi}_1^*)^T \cdot (\mathbf{m} - \mathbf{a}^*) = 0, \tag{20b}$$

$$(\boldsymbol{\xi}_2^*)^T \cdot (\mathbf{a}^* - \mathbf{P}_{\max}) = 0, \tag{20c}$$

$$\xi_3^* \cdot \left[\phi_{\mathrm{MI}} - \sum_{n=0}^{M_c-1} \log\left(1 + \frac{a_n^*}{l_n}\right)\right] = 0, \tag{20d}$$

$$m_n \leq a_n^* \leq P_{\max,n}, n \in \mathcal{M}_n, \tag{20e}$$

$$\boldsymbol{\xi}_1^* \geq \mathbf{0}, \tag{20f}$$

$$\boldsymbol{\xi}_2^* \geq \mathbf{0}, \tag{20g}$$

$$\xi_3^* \geq 0. \tag{20h}$$

According to the above KKT conditions, if $\mathbf{a}^*$ is the optimal solution, we can get:

$$a_n^* = \frac{\xi_3^*}{1 - \xi_{1,k}^* + \xi_{2,k}^*} - m_n. \tag{21}$$

It is apparent from (20a)-(20c) that the optimality conditions can be separately investigated for three possibilities regarding the optimal allocated power in each subcarrier. At the optimality, each subcarrier can be allocated either with minimum transmit power ($a_n^* = m_n$), with maximum power ($a_n^* = P_{\max,n}$), or with a power between these two extreme cases ($m_n < a_n^* < P_{\max,n}$).

i) If $m_n < a_n^* < P_{\max,n}$, then $\xi_{1,k}^* = \xi_{2,k}^* = 0$, we have:

$$m_n < \xi_3^* - m_n < P_{\max,n} \iff \xi_3^* - P_{\max,n} < l_n < \xi_3^* - m_n. \tag{22}$$

Then, a_n^* can be computed as:

$$a_n^* = \xi_3^* - l_n. \tag{23}$$

The remaining step is to compute the value of ξ_3^*. The optimal ξ_3 is such that it satisfies the following condition:

$$\sum_{n=0}^{M_c-1} \log\left(1 + \frac{a_n^*}{l_n}\right) \geq \phi_{\mathrm{MI}}. \tag{24}$$

ii) If $a_n^* = m_n$, then $\xi_{1,k}^* > 0$, $\xi_{2,k}^* = 0$, we can obtain:

$$a_n^* + l_n = \frac{\xi_3^*}{1 - \xi_{1,k}^*} > \xi_3^* \iff l_n > \xi_3^* - m_n. \tag{25}$$

Then, a_n^* can be given by:

$$a_n^* = m_n. \tag{26}$$

iii) If $a_n^* = P_{\max,n}$, then $\xi_{1,k}^* = 0$, $\xi_{2,k}^* > 0$, we can have:

$$a_n^* + l_n = \frac{\xi_3^*}{1 + \xi_{2,k}^*} < \xi_3^* \iff l_n < \xi_3^* - P_{\max,n}. \tag{27}$$

Then, a_n^* is obtained as:

$$a_n^* = P_{\max,n}. \tag{28}$$

Therefore, the globally optimal waveform design solution can be obtained as (17), which completes the proof. ■

According to *Proposition 1*, it can be seen that the conditional MI $\mathcal{I}(r(t); g(t)|s_{\rm rc}(t))$ is monotonic increasing function of a_n, while the second derivative of $\mathcal{I}(r(t); g(t)|s_{\rm rc}(t))$ is strictly decreasing in a_n. Thus, the monotonic property implies that there does exist a unique solution a_n^* that satisfies **C2** between the given lower and upper bounds m_n and $P_{\max,n}$. On the other hand, the value of ξ_3^* can be determined by solving (24). Since there does not exist the closed-form solution for (24), ξ_3^* can be obtained from a general one-dimensional grid search over ξ_3. Therefore, the well-known bisection search approach can be employed to solve it.

Overall, by formulating the KKT optimality conditions, we convert the resulting convex optimization problem (**P2**) into a nonlinear equation solving problem, and then utilize the bisection search approach to tackle with it. For the sake of clarity, the pseudo-code of the LPI-based integrated OFDM waveform design strategy is summarized in **Algorithm 1**, according to which we can get the optimal OFDM waveform design results for the IRCS. Additionally, the bisection search method is omitted here for brevity, and the readers can refer to [14] for details. Physically speaking, the output of **Algorithm 1** is actually the optimal waveform design results, achieved with the assumption that the IRCS knows the exact characteristics of the PSDs of target and colored noise.

Algorithm 1 The Detailed Steps of the Proposed Strategy

```
Input: Set φ_MI, P_max,n, C_min, M_c, and iterative index ite = 1
Output: a_n^*, ∀n ∈ M_n
for n = 1, ···, M_c do
    Calculate a_n^(ite) by solving (17);
    Calculate the achieved MI Σ_{n=0}^{M_c−1} log(1 + a_n^(ite)/l_n);
    Obtain ξ_3^(ite+1) via bisection search;
end
Output the final solution.
```

Remark 2: It is noteworthy that the iterative steps of bisection search approach to find ξ_3^* can be carried out by employing one-dimensional search over the parameter ξ_3. For a predefined $\phi_{\rm MI}$, the bisection search method requires $\mathcal{O}\left(\log_2\left(\frac{\xi_{3,\max}-\xi_{3,\min}}{\delta}\right)\right)$ iterations to converge [14], [26]. Hence, the computational complexity of **Algorithm 1** is expressed by $\mathcal{O}\left(M_{\rm c}\log_2\left(\frac{\xi_{3,\max}-\xi_{3,\min}}{\delta}\right)\right)$. Obviously, the execution of **Algorithm 1** converges to the optimum solution much more quickly when compared to the exhaustive search technique. In addition, it is important to note that the proposed **Algorithm 1** can guarantee the optimum solution and converge to KKT point.

IV. PERFORMANCE EVALUATION RESULTS AND DISCUSSION

In this section, the waveform design results and the LPI performance of the proposed strategy are evaluated by means of computer simulations employing the following assumptions as well as specific values for the various system parameters.

A. NUMERICAL SETUP

For the simulations, we consider a system model similar to Figure 1, which consists of an IRCS, a target and a downlink communications user. By imposing the conditional MI and data information rate constraints, we can design the optimal transmit OFDM waveform that minimizes the total radiated power using optimization problem (**P2**) and **Algorithm 1**. Unless otherwise stated, we utilize the following default for the system parameters. In all the simulations, the carrier frequency of the IRCS is $f_{\rm o} = 3$ GHz. The RF bandwidth is set to be 512 MHz, which is equally divided by $M_{\rm c} = 128$ subcarriers, and thus $\Delta f = 4$ MHz. For convenience, we set the parameters of the IRCS as provided in Table 1. As previously mentioned, to solve the resulting optimization problem (**P2**), it is assumed that the IRCS knows the perfect characteristics of the PSDs of target and colored noise by sensing itself with a spectrum analyzer [14]. Thus, the power of surveillance channel is illustrated in Figure 2, and the PSD of colored noise is shown in Figure 3.

TABLE 1. The parameters of the IRCS.

Parameter	Value	Parameter	Value
G_t	30 dB	G_r	30 dB
G_s	0 dB	$R_{\rm rc}$	100 km
$R_{\rm c}$	10 km	$P_{\max,n}(\forall n)$	600 W

B. WAVEFORM DESIGN RESULTS

Figure 4 depicts the LPI-based optimal OFDM waveform design results with different thresholds of target estimation and data information rate, which give insight about the transmit power allocation for the LPI performance improvement of IRCS. The results clearly show that the OFDM waveform design is determined by the PSDs of target and colored noise. To be specific, to guarantee a predetermined target characterization performance $\phi_{\rm MI}$, our proposed strategy only concentrates the transmit power resource to the subcarriers with the best channel condition, that is, the largest target PSD and the weakest noise power (see the waveform design results for the subcarriers between 0 and 20, 101 and 127 for example). On the other hand, for a desired data information rate $C_{\min}$, the proposed scheme tends to distribute more transmit power to the subcarriers with less noise power (see the waveform design results for the subcarriers between 20 and 100 for example). In such a case, the overall MI value is averaged, and the data information rate can be achieved. As expected, it can also be observed from these results that the total transmitted power is increased as the system requirements for target

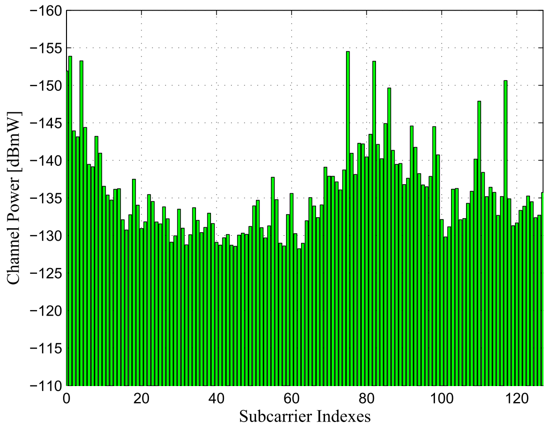

FIGURE 2. **The power of surveillance channel.**

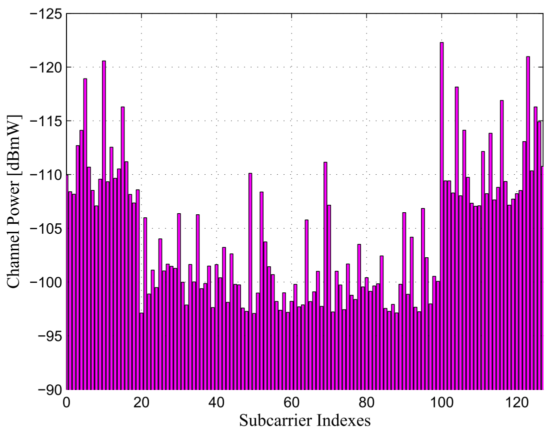

FIGURE 3. **The PSD of colored noise.**

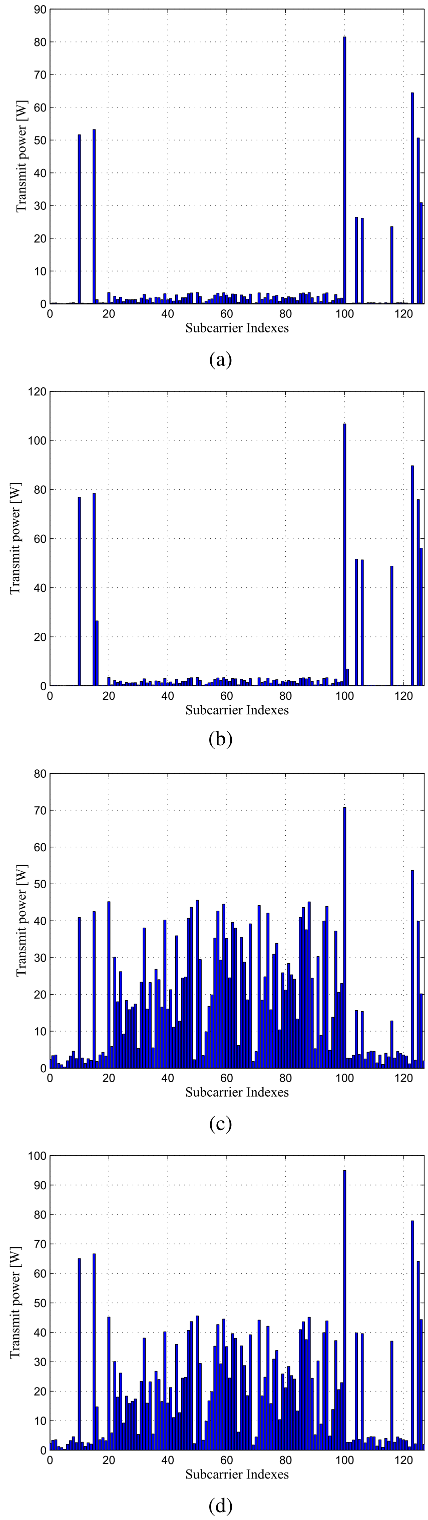

FIGURE 4. **LPI-based optimal OFDM waveform design results with different thresholds of target estimation and data information rate: (a) $\phi_{MI} = 7.5$ nats, $C_{min} = 2.5$ nats; (b) $\phi_{MI} = 10$ nats, $C_{min} = 2.5$ nats; (c) $\phi_{MI} = 7.5$ nats, $C_{min} = 5$ nats; (d) $\phi_{MI} = 10$ nats, $C_{min} = 5$ nats.**

estimation and data information rate become more demanding (the threshold values of ϕ_{MI} and C_{min} increase). This happens because with the increase of ϕ_{MI} and C_{min}, there is more power resource that is needed at the transmitter to satisfy the desired target estimation performance and data information rate, while the power allocation tendencies remain the same. Therefore, it can be concluded that, to meet the requirements of both radar and communications functions, the IRCS appropriately allocates its power resource to different subcarriers, and then the LPI performance can efficiently be enhanced.

C. LPI PERFORMANCE EVALUATION

In traditional IRCS, none of the prior knowledge is utilized for the integrated OFDM waveform design. In this scenario, the transmit power resource is uniformly allocated to different subcarriers to fulfill the requirements of both radar and communications applications. Herein, to better express the superiority of the proposed optimal OFDM waveform design strategy, we first compare the total radiated power results between our proposed strategy and a benchmark in Figure 5, where the benchmark stands for the uniform power allocation-based OFDM waveform design method. To guarantee fairness, the threshold values of MI and data information rate are set to be the same in both strategies. It can be seen from Figure 5 that our proposed strategy transmits the minimum power. More specifically, the LPI-based optimal

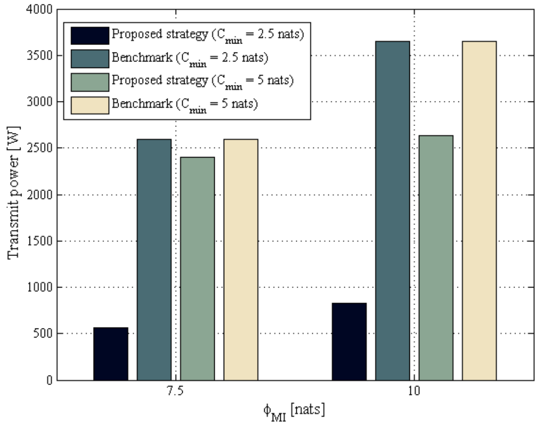

FIGURE 5. Comparison of the total radiated power for the proposed strategy and the benchmark with different threshold of data information rate.

OFDM waveform design strategy may save about $7\% - 77\%$ power consumption when compared with the benchmark. The results also show that the total radiated power of IRCS is enlarged as $\phi_{\rm MI}$ and $C_{\min}$ increase, which is in agreement with the previous statement in Section IV-B. Thus, better target estimation performance and data information rate indicates that the constraints in optimization problem (**P0**) are more likely to be satisfied with a larger radiated power consumption.

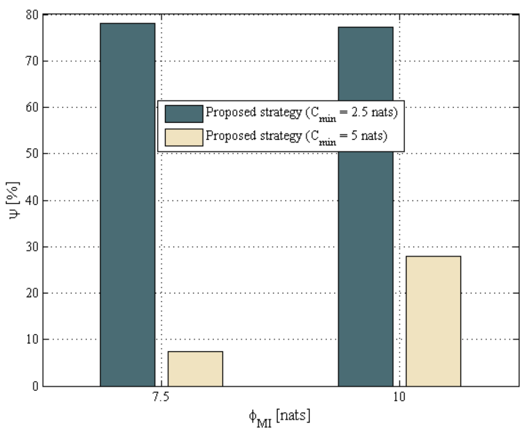

FIGURE 6. Comparison of the improvement of intercept probability for the proposed strategy and the benchmark with different threshold of data information rate.

Moreover, to illustrate the LPI performance enhancement of the proposed strategy, a parameter ψ, namely the improvement of intercept probability of an IRCS, is defined and adopted as a metric to compare with the benchmark in Figure 6 for different threshold of data information rate, which can be given by:

$$\psi = \frac{p_{\rm Psd} - p_{\rm Bch}}{p_{\rm Bch}} \times 100\%, \tag{29}$$

where $p_{\rm Psd}$ and $p_{\rm Bch}$ represent the values of intercept probability by employing our proposed strategy and the benchmark, respectively. It is indicated in [38] that the intercept probability is a function of several parameters, such as the dwell time, interceptor search time, radar transmitted power, and so on. Readers can refer to reference [38] for detailed calculation of intercept probability. The definition in (29) implies that the larger ψ is, the better LPI performance of IRCS is. An intuitive explanation is that, the waveform design results with smaller power dissipation can obtain larger value of ψ, which means better LPI performance of IRCS. In Figure 6, we can observe that the proposed optimal waveform design strategy utilizes a small quantity of transmit power resource to satisfy the requirements of both radar and communications applications, and thus yields an improved LPI performance for IRCS. Also, for a specified MI threshold value, the value of ψ is reduced as $C_{\min}$ goes up, which is due to the fact that more transmit power is radiated to guarantee the desired data information rate. In addition, it is important to notice that when $C_{\min} = 2.5$ nats, the value of ψ is decreased as $\phi_{\rm MI}$ increases. However, when $C_{\min} = 5$ nats, ψ is increased as $\phi_{\rm MI}$ goes up. The reason is that when the threshold $C_{\min}$ increases, the transmit power resource of IRCS is assigned to more subcarriers to satisfy the predefined requirement of data information rate. In such a case, the achievable value of MI is averaged, and thus the power consumption can be reduced, which results in the increase of ψ. Overall speaking, the above simulation results confirm the superiority of the proposed LPI-based optimal OFDM waveform design strategy, since it always yields better LPI performance when compared to that of the benchmark.

D. DISCUSSION

Combining the above results in Figures 4-6, it should be highlighted that our proposed waveform design strategy is particularly attractive for practical implementation for the reasons as follows [29]:

1) Intuitively speaking, in the waveform design process, the LPI-based optimal OFDM waveform design strategy for IRCS is more likely to allocate waveform power to the subcarriers with larger target PSD and less noise power. In this scenario, the achievable MI and data information rate can be averaged. Increasing the threshold values of the conditional MI and data information rate can enlarge the total radiated power in the proposed waveform design strategy, whereas the power allocation tendencies remain the same.
2) The proposed integrated OFDM waveform design strategy can evidently enhance the LPI performance of IRCS compared with the benchmark, while satisfying the desired requirements of target characterization and data information rate.
3) The threshold values of the conditional MI and data information rate are controllable, which indicates that the corresponding threshold values of the target estimation and communication requirements can be adjusted for different application scenarios.

4) The proposed integrated OFDM waveform design strategy can straightforwardly be expanded to the MIMO case composed of multiple transceivers and multiple targets, which will be our future research.

V. CONCLUSION REMARKS

An IRCS has more advantages over individual radar and communications systems, which can reduce the system size, weight, power consumption, and mutual interference; also, the RF spectrum efficiency of the underlying system can be improved. Therefore, the LPI-based optimal OFDM waveform design for an IRCS is proposed. The basis of this scheme is to utilize optimization technique to design the transmitted OFDM waveform of IRCS in order to enhance its LPI performance. It is shown that the resulting waveform design problem is convex and can analytically be solved through the bisection search technique. In this case, the optimal solution can easily be obtained to satisfy the requirements of a real-time system. Various performance evaluation results obtained by the means of numerical simulation experiments have demonstrated that the proposed strategy can achieve better LPI performance when compared to the benchmark, while maintaining the predetermined MI and data information rate threshold values. More specifically, the results show that more transmit power is allocated to the subcarriers which have larger target PSDs and suffer less noise power levels.

In our future work, we plan to find a joint solution to the optimization problem, in which the transmit beamforming and integrated OFDM waveform will be jointly optimized to find the optimal solution to the optimization problem built in this study. Moreover, the current signal model, optimization problem, and the solution do not take in consideration the effects of multiple transceivers in IRCS and multiple targets that may act as passive interceptors. Therefore, we plan to extend the signal model to take into consideration multiple transceivers and multiple targets, which will also be one of our future research directions.

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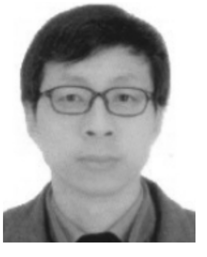
CHENGUANG SHI was born in Luoyang, China, 1989. He received the B.S. and Ph.D. degrees from the Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2012 and 2017, respectively. He is currently a Lecturer with the Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing University of Aeronautics and Astronautics. His main research interests include low probability of intercept optimization, radar network, adaptive radar waveform design, and target tracking.

FEI WANG received the M.S. and Ph.D. degrees from Jilin University in 2003 and 2006, respectively. He is currently an Associate Professor with the Nanjing University of Aeronautics and Astronautics.

SANA SALOUS (SM'95) received the B.E.E. degree from the American University of Beirut, Beirut, Lebanon, in 1978, and the M.Sc. and Ph.D. degrees from Birmingham University, Birmingham, U.K., in 1979 and 1984, respectively. After four years as an Assistant Professor with Yarmouk University, Irbid, Jordan, she was a Research Fellow with Liverpool University, U.K., for one year at which point she took up a lectureship at the University of Manchester Institute of Science and Technology, U.K., in 1989, where she was subsequently a Senior Lecturer and then a Reader. Since 2003, she has been the Chair in communications engineering with Durham University, U.K., where she is currently the Director of the Centre for Communication Systems. Her research interests include radio channel characterization in various frequency bands ranging from skywave in the HF band to millimeter bands up to 90 GHz, the design of radar waveforms, novel radio channel sounders, and radar systems for radio imaging. She is a fellow of the Institution of Engineering and Technology and of the International Union of Radio Science. She was the Chair of Commission C on radio communication and signal processing systems of the International Union of Radio Science (2014–2018). She is currently an Editor of the journal *Radio Science*.



JIANJIANG ZHOU received the M.S. and Ph.D. degrees from the Nanjing University of Aeronautics and Astronautics (NUAA) in 1988 and 2001, respectively. He is currently a Professor and the Director of the Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, NUAA.

His main research interests include aircraft radio frequency stealth, radar signal processing, and array signal processing.