Hybrid Beamforming in mmWave Dual-Function Radar-Communication Systems: Models, Technologies, and Challenges

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Abstract—As a promising technology in beyond-5G (B5G) and 6G, dual-function radar-communication (DFRC) aims to ensure both radar sensing and communication on a single integrated platform with unified signaling schemes. To achieve accurate sensing and reliable communication, large-scale arrays are anticipated to be implemented in such systems, which brings out the prominent issues on hardware cost and power consumption. To address these issues, hybrid beamforming (HBF), beyond its successful deployment in communication-only systems, could be a promising approach in the emerging DFRC ones. In this article, we investigate the development of the HBF techniques on the DFRC system in a self-contained manner. Specifically, we first introduce the basics of the HBF based DFRC system, where the system model and different receive modes are discussed with focus. Then we illustrate the corresponding design principles, which span from the performance metrics and optimization formulations to the design approaches and our preliminary results. Finally, potential extension and key research opportunities, such as the combination with the reconfigurable intelligent surface, are discussed concisely.

I. INTRODUCTION

In the emerging beyond 5G (B5G) and sixth-generation (6G) networks, sensing capabilities have been recognized as a novel feature. The embedding of sensing functionality into wireless communication networks leads to the so-called dual-function radar-communication (DFRC), which has become research area with significant activity of late [1]. Unlike the solutions for co-existence of radar and communications, which mainly target spectrum sharing, DFRC integrates the radar and communication functionalities into a single platform under the umbrella of a unified signal processing framework. Not only can it improve the energy and spectrum efficiencies, but can also reduce hardware and signaling costs. In addition, sensing capabilities can be used to enhance the performance of the wireless communication network itself by providing optimization input for network steering [2].

With the expansion of spectrum allocations towards higher frequencies, such as millimeter-wave (mmWave) and terahertz (THz) bands, severe free-space path loss must be considered to build DFRC systems for B5G and 6G. Massive multiple-input multiple-output (MIMO) with a large number of antennas is one of the key technologies to cope with this shortcoming. Nevertheless, if each antenna is equipped with a separate radio frequency (RF) chain to perform fully digital beamforming, the hardware cost and energy consumption could be prohibitive. Hence, hybrid beamforming (HBF), which shows great success in wireless communication [3], has also been recognized as a promising trend for DFRC system development.

Essentially, the HBF technology uses a combination of low-dimension digital beamforming and high-dimension analogy beamforming to attain a judicious trade-off between the system performance and hardware cost [4]. Specifically, only a small number of RF chains are deployed for digital beamforming, but the analogy beamforming is realized by many cost-efficient phase shifters (PSs). Although HBF has been widely studied for communications, it is still in its infancy for DFRC and further investigations are expected. Research questions like, how to model the HBF problem for DFRC and how the models impact on the principles and methodologies on system design are yet to be addressed. This dual-functional system requires new signal processing approaches. Additionally, practical constraints imposed on the DFRC system and coupling relationship between digital and analog beamformers will bring challenges to tackle high-dimension and non-convex optimization problems involved in various designs.

While the extension of HBF from communication to DFRC is natural, it demands significant effort to pave its way for incorporation in future communication networks. Building on the state-of-the-art in this area, the afore-mentioned issues regarding on the models, technologies and challenges in HBF based DFRC systems will be discussed in this paper. We hope this work can provide the reader an overview of this important topic and encourage research towards further integration of sensing and communications in large antenna systems.

II. BASICS OF HYBRID BEAMFORMING IN DFRC

In this section, we introduce the basics of HBF in DFRC system, which will serve as the preliminaries for next sections. Specifically, we introduce the system model of HBF based DFRC system, followed by detailed DFRC receive modes.

A. System Model of HBF based DFRC

Fig. 1 gives the overview of the HBF-based DFRC system. There are $N_{RF}$ RF chains and $N_r$ antennas at the transmitter. For the $U$ downlinks, each of them has $N_{RF}^U$ RF chains and $N_r^U$ antennas. For data transmission, the vector of all data symbols $s$ has a length of $N_s$ and each symbol is
usually assumed to be statistically independent. The symbols to be transmitted are processed by a digital beamformer $F_D$, then up-converted to RF domain and precoded by an analog beamformer $F_{RF}$, which is realized by PSSs.

For analog beamformers, there are three common architectures, i.e., full connection, partial connection and dynamic connection, as depicted in Fig. 2. More specifically, in the full connection architecture, each RF chain is connected to all antennas via PSSs. For the partial connection structure, each RF chain connects to a fixed subset of antennas. As for the dynamic connection structure, each RF chain can dynamically connected a subset of antennas. A qualitative comparison of the analog beamformer structures is shown in Fig. 2(d), which indicates that by properly choosing the PSSs network structure, the DFRC can achieve a good trade-off between performance and energy efficiency.

For communications, to estimate the symbols to user $u$, the received signal will be processed by both the analog and digital combiners as shown in Fig. 1. With the existence of noise on the receiver, the signal to user $u$ is processed by the analog combiner $W_{RF,u}$ followed by the digital combiner $W_{DFRC}$. Thus, by designing the HBF on both the transmit and receive sides jointly, a satisfying symbol error rate can be ensured [6].

For radar sensing, the transmit beampattern should concentrate on the potential directions of the targets of interest while suppressing its sidelobes. In the context of HBF, the transmit beampattern of the emitted signal is a function of the digital and analog beamforming matrices. Thereby, by designing the HBF properly, a desired transmit beampattern can be achieved. Additionally, for radar parameter estimation, if we consider a multi-carrier signaling scheme, we can obtain $KM_r$ virtual data vectors by matching filtering the received signals at all the $K$ subcarriers, when the radar receiver has $M_r$ RF chains. Two important issues should be considered for the virtual model. (i) Increasing the number of carriers and using the virtual aperture are advantageous to improve the resolution of parameter estimation, e.g., direction-of-arrival (DOA) estimation. (ii) More carriers will result in less power per virtual element, which in turn leads to affecting the DOA estimation performance [5].

1 The HBF design requires a known CSI, which is challenging to obtain for the HBF-based system due to the fact that the digital baseband has no direct access to the entries of the CSI matrix. Compressed sensing-based methods can be used to achieve the channel estimation due to the sparse property of mmWave channels in the angle domain.

B. Receiving Modes

As shown in Fig. 3 to support the implement of DFRC, the system can work in monostatic, bistatic and distributed receive modes, which are introduced as follows.

Fig. 1. Overview of the hybrid beamforming based DFRC system.

Fig. 2. Comparison of the full, partial and dynamic connection analog beamformer. (a) Full Connection Structure; (b) Partial Connection Structure; (c) Dynamic Connection Structure; (d) Performance comparison of the three structure.

Fig. 3. Diagrams of (a) Integrated Transceiver Mode, (b) Collocated Transmit-Receive Mode, (c) Bistatic Receive Mode and (d) Distributed Receive Mode.

Integrated Transceiver Mode: In this mode, the base station transmitter and radar receiver share the same hardware platform, as shown in Fig. 3(a), where a transmitter emits the DFRC waveform to a user, and receives echoes from the
different metrics need to be considered. (1) Particularly, the as distance, velocity and directions. For the diverse radar tasks, the targets of interest, and estimate relevant parameters, such functionalities while optimizing a certain tradeoff.

Collocated Transmit-Receive Mode: In this mode, the transmitter and radar receiver share the same array, the system can only work under pulsed mode. This mode has significant advantages of low hardware complexity and avoiding interference caused by the leakage from transmitter, but has shortcomings of blind spots in short range and low communication rate. The pulse width determines the blind range. In addition, since the transmitter and radar receiver share the hardware, the constraints on radar receiver should be taken into account when designing the analog precoder.

Bistatic Receive Mode: In this mode, the radar and the communication receiver share the same hardware, thereby forming a bistatic sensing mode. This mode can support continuous-wave signal and has a advantage of better localization accuracy compared to the earlier monostatic case. However, this mode is limited in the waveform to preamble and pilots. Additionally, since one array supports both radar and communication receivers, the digital combiner can be optimized for each function, while the analog combiner is optimized considering both radar and communications. It is noted that this mode also includes the uplink sensing, in which the transmitted signal is from users, and it can be also viewed as the passive sensing [6].

Distributed Receive Mode: Herein, the sensing signal can be received by multiple receivers after being backscattered by the target. This mode can be viewed as multiple bistatic receiving pairs. This model offers spatial diversity to achieve improved target detection performance and better localization accuracy via a cooperative processing mechanism among different receivers [7]. The HBF design for this DFRC system should consider the multi-user interference (MUI).

III. DESIGN PRINCIPLES OF HBF IN DFRC SYSTEM

In this section, the key performance metrics in designing the HBF for the DFRC system are discussed first, followed by the potential design approaches. Such designs are based on the formulated system performance metrics and the available communication channel state information (CSI), radar detection scenario and system requirements.

A. Performance Metrics

In a DRFC system, the HBF is expected to simultaneously improve the performance of both radar and communication functionalities while optimizing a certain tradeoff.

Radar Performance Metrics: Radar systems aim to detect the targets of interest, and estimate relevant parameters, such as distance, velocity and directions. For the diverse radar tasks, different metrics need to be considered. (1) Particularly, the target detection performance is quantified by probability of detection (\(P_d\)) under a certain probability of false alarm (\(P_f\)). It is shown that the detection performance under Gaussian noise is positively correlated with the signal-to-interference-plus-noise ratio (SINR), which also depends on the beam-pattern gain. (2) For multi-target detection scenario, desired properties of the beampattern, include multiple mainlobes, good peak sidelobe level (PSL) or integrated sidelobe level (ISL). (3) For parameter-estimation tasks, the Cramér-Rao lower bound (CRLB), which determines the lower bound on estimation accuracy for unbiased estimators, is considered. In typical radar application, several parameters needed to be estimated e.g., range, velocity, and direction. (4) For target characterization scenario, mutual information (MI) is also a popular metric, whose maximization will improve the target characterization capability of a radar system.

Communication Performance Metrics: The goal of communication systems is to enhance the rate transfer of error-free communication data over a fixed bandwidth, this goal is commonly known as the quality-of-service (QoS). The performance metrics corresponding to the QoS includes: spectral efficiency (SE), the mutual information symbol error rate (SER), energy efficiency (EE) and mean square estimation error (MMSE). Apart from these metrics, for the quadrature amplitude modulation (QAM), the constellation range can be also selected as the figure of metric to minimize the average SER in block HBF precoding.

B. Multi-Objective Optimization (MOO) Formulation

Typically, the problem of HBF design for the DFRC system consists of a number of objective functions, i.e., radar and communication criteria, and is associated with a number of constraints. For a MOO problem, the choice of the objective function has a significant impact on the trade-off performance and hence needs to be selected appropriately.

Solving an MOO problem (MOOP) implies that one should find the Pareto set of the MOOP. Numerous studies have been shown that methodologies to solve a MOOP is usually based on converting the MOO into a single-objective optimization (SOO) problem, whose optimal solution has also been proved to be in the Pareto set of the MOOP [10]. These methodologies usually contain the weighted-sum, the \(\epsilon\)-constraints, and min-max formulations. The detailed illustrations are provided below.

Weighted-Sum Formulation: In the weighted-sum model, the multiple performance criteria are converted into a single objective by multiplying each criterion with a given coefficient (weight). Due to the fact that different criteria may represent different performance and have different units, the normalization of each metric must be undertaken prior to exploiting this model for solving the MOOP. Subsequently, we select the weights for different criteria to achieving the expected trade-off. It should be noted that the optimal solution of the weighted-sum problem is a Pareto-optimal one of the MOOP.\(^\dagger\)

\(^\dagger\) It is proved in [5] that for a fully-digital receiver, the maximization of SE is equivalent to maximizing MI.\(^\ddagger\)

\(^\ddagger\) Actually, when the user adopts the MMSE receiver, the maximization of SE equals to the minimization of the MMSE [9].
The weighted-sum model is a straightforward way to handle with the MOOP. The weights are non-negative and add up to 1. Nevertheless, a drawback of the weighted-sum model is that the objective is sensitive to the choice of the weights, and determination of suitable weights to attain the satisfactory balance is difficult; a large number of trials with different choices of weights need to be made to generate a satisfactory solution.

\( \epsilon \)-Constraints Formulation: The \( \epsilon \)-constraints model produces a SOO problem, where only one objective function is minimized while tackling the remaining objectives as constraints. It is proved in [10] that the optimal solution obtained by the \( \epsilon \)-constraints method is a weak Pareto optimum of the original MOOP, and under certain conditions, this solution even attain Pareto optimality. Compared to the weighted-sum method, the \( \epsilon \)-constraints method has a simpler objective but more complicated constraints; this usually make the problem more challenging to solve. Similar to the choice of weights in the weighted-sum method, there is no prior scheme corresponding to adjusting \( \epsilon \). This method is normally applied to scenarios where focus lies on only one metric while the remaining ones are user-specified in advance.

Min-Max Formulation: The min-max model generates the SOO problem with \( \max_{x,i} f_i(x) \) being the objective function and \( f_i(x) \) being the \( i \)th objective in MOOP. A common approach to settle this problem is to introduce another variable \( \eta \) to convert the tricky min-max objective into a simpler one, as \( \min_{x,\eta} \eta \), s.t. \( f_i(x) \leq \eta, \forall i \). However, introducing additional constraints usually increases the complexity of the problem-solving. It has been shown in [10] that the min-max method provides a necessary condition for Pareto optimal solution, but a sufficient condition only for a weak Pareto optimality. When the obtained solution is unique, it is Pareto optimal.

C. Design Approaches

The problem of the HBF design for the DFRC system is typically nonconvex, which makes it challenging to obtain the optimal analog and digital beamformer matrices directly. The main reasons are as follows:

- Analog and digital precoder/combiner are coupled in the objective and constraints, which makes the resultant problem nonconvex.
- Generally, taking both radar and communication metrics into consideration makes the objective nonlinear, which adds to the challenge of finding the HBF matrices.
- Additionally, the constant modulus constraints on analog precoder/combiner is nonconvex, which also adds to the difficulty and complexity of the problem.

Two approaches have the potential to address these difficulties and find suboptimal solutions. It is worth mentioning that there are some works in combining both learning and model-based strategies to form a hybrid solving approach [11].

Indirect Two-Stage Approach: This approach (c.f. [3]), which is based on the two-stage optimization strategy, is capable of designing the HBF in an indirect manner. In this method, the fully digital beamformer \( \mathbf{F}^d \) is firstly optimized by replacing the hybrid beamformer with fully digital one in the original problem, and then the hybrid beamformer is designed by minimizing the Euclidean distance to the obtained fully digital one. By doing so, the objective of the indirect problem is much less complicated than the original one, resulting in low complexity in computations. However, due to the indirect design, the achieved hybrid beamformer will suffer from a performance loss. Besides, it is noted that the two-stage method is not applied to solve the problem with \( \epsilon \)-constraints model, since the achieved hybrid beamformer that approximates the fully-digital one cannot satisfy the constraints on other metric.

Direct Decoupling Approach: As mentioned earlier, the main difficulty in HBF design is the coupling between the analog and digital precoders/combiners. This motivates us to first decouple the hybrid beamformer to simplify the problem. For example, in [12], the objective function is a weighted summation of the multi-user MMSE and radar spatial spectrum matching error (SSME). To decouple the analog and digital beamformers, a set auxiliary variables \( \mathbf{Y}_{k,u} = \mathbf{F}_{RF}^u \mathbf{F}_k \) are introduced, such that the complex objective function can be decomposed into \( UK \) sub-functions, and each sub-function depends only upon a variable \( \mathbf{Y}_{k,u} \). This enable us to iteratively optimize \( (\{\mathbf{Y}_{k,u}\}, \mathbf{F}_{RF}, (\mathbf{F}_k)) \) under the consensus alternating direction method of multipliers (consensus-ADMM) framework [13].

IV. PERFORMANCE ANALYSIS

In this section, we illustrate the performance of the DFRC system with different HBF architecture and design approaches through numerical simulations.

We first demonstrate the trade-off of the DFRC system between the radar and communication functionalities as shown in Fig.4. In the considered scenario, the optimization problem is formulated in the weighted-sum form. By tuning the weight parameters with a small stepsize, we obtain the Pareto bounds. It is observed that the radar mutual information decreases monotonically with an increase in the communication mutual information under all the structures, which reveals the Parato optimality inside the DFRC system on the radar and communication aspects. This Parato optimality further implies that to achieve an appropriate trade-off between sensing and communication, selection of the weight parameters is crucial. Moreover, these results also indicate that an appropriate choice of the HBF structure can trade-off between the hardware complexity and DFRC performance.

Next, we provide simulation results of different hybrid beamforming design schemes as shown in Fig.5. In this simulation, we consider the wideband OFDM based DFRC system serving multiple downlink users and detecting radar targets, where the simulation setting and more details can be found in [12]. For the comparison purpose, the DFRC system with the fully digital structure is included as the performance upper bound. It is clear to see that the two-stage method suffers from severe performance loss in terms of both radar beampattern and communication spectral efficiency. In contrast, with the direct design, hybrid beamforming for the DFRC system achieve better performance consistently at all SNR levels.
Thus, the power consumption of active RF chains is given by
structure, the RF chain consumption caused by DAC
RF converter

\[ P_{RF} = 4 \text{ Watts} \]

Consider the communication performance of the DFRC-BS system. The main-lobe region

\[ \Omega_{main} = [-0.7891, -0.337] \cup [0.0939, 0.657] \]

(a) The space-frequency spectra for Fully Digital case; (b) The space-frequency spectra for CADMM case; (c) The space-frequency spectra for Two Stage case; (d) The spectral efficiency versus the SNR for different methods.

V. NEW FRONTIERS IN ADVANCED HBF DFRC SYSTEMS

From a practical perspective, HBF is a promising technology to be implemented in the upcoming DFRC system. However, to achieve both the sensing and communication functionalities, the vanilla HBF might not fulfill the requirements and achieve optimal tradeoffs. Hence, advance HBF techniques should be developed on various aspects such as architecture, signal processing, and technology convergence; these will be discussed in this section.

A. HBF in Wideband DFRC Systems

In order to maintain reliable robustness against multipath fading for communication and to improve estimation accuracy for sensing, wideband is necessary. Specifically, wideband OFDM system can be regarded as a special case of multi-carrier system, when the number of carriers is very large, the system presents the wideband property. Different from the narrowband model, the delay of wideband system is related to the frequency, this results in frequency-dependent beampattern [12]. Moreover, for the analog beamformer, different frequencies need different phase shifts. As a result, the standard HBF architecture based on PSs cannot deal with the beam-squint problem caused by the large number of antennas and bandwidth, as well as the small number of RF chains. The beam-squint problem will lead to the beam pointing offset and beam split effect, in which different subcarriers have different spatial directions. The beam-squint problem will result in a situation where only the beams around the expected subcarrier are able to attain a high gain, while the beams at other subcarriers suffer from a serious loss in gain, which has not been well investigated in wideband HBF-based DFRC systems [11]. In order to mitigate this effect, combining the time delay network with analog PSs is able to be introduced to general frequency-dependent-like PSs to form the frequency-dependent beams. Therefore, research on the delay-phase hybrid beamforming design and corresponding performance analysis should be carried on in future work for wideband DFRC systems.

B. HBF in DFRC Systems With Low-Resolution ADCs and DACs

In mmWave systems, the high sampling rate and high quantization bit of ADCs and DACs will result in high power consumption and cost (e.g., a high resolution ADC ≥ 8 bits consumes several Watts [14]). The HBF structure is capable of reducing the power consumption and cost via adopting a limited of RF chains. Besides the HBF structure, the utilization of low-resolution ADCs/DACs is another ingredient for mmWave system. Although the low-resolution ADCs/DACs have advantages of saving the cost and power consumption, they may lead to severe performance loss. In communication applications, with low-resolution ADCs, the performance of HBF and fully digital beamforming has been compared. The results show that at low SNR regions, the fully digital beamforming with low resolution ADCs achieves the same performance to the HBF with ideal ADCs. In addition, the HBF with coarse quantization attains better performance-EE trade-off. However, there is a lack of research works on joint optimization of HBF and ADCs/DACs resolutions for mmWave DFRC systems. Further, the analysis of low-resolution ADCs/DACs in DFRC will help us come to a new understanding related to the HBF design issues, but which is almost blank currently. For example, in a specific DFRC application, it is not trivial to determine the appropriate RF chain number, bit-resolution of ADCs/DACs and PS resolutions to achieve an excellent trade-off among radar performance, communication performance and hardware efficiency.

C. RIS-Assisted HBF DFRC Systems

Reconfigurable Intelligent Surface (RIS) consists of multiple passive elements, each of which can introduce phase shift.
independently and hence alter the radio propagation environment. From a signal processing perspective, it is essentially shaping a passive beamforming on the impinging signals. Therefore, it is appealing to integrate RIS into the DFRC system to enhance system performance including beam accuracy, coverage and spatial diversity, etc. The resulting problems are usually formulated as a joint design of both the active (i.e., HBF on the station) and passive (i.e., RIS) beamforming, which requires efficient optimization algorithms especially in the context of large-scale DFRC deployment. Furthermore, RIS has been evolving from the standard passive, discrete and narrowband case to an advanced one which exhibits active, holographic and wideband properties. Correspondingly, the joint design of RIS and HBF becomes even more challenging, thereby warranting an investigation in the HBF DFRC settings. For example, the beam-squint effect overcome by wideband HBF shall re-appear, unfortunately, after reflecting by a narrowband RIS. Apart from the design aspects, it is meaningful from an analytical perspective to pursue the goal of proving the theoretical bound on performance gain in such a system—a matter less investigated in literature compared to the design aspects.

D. OTFS Modulated HBF DFRC Systems

In high-mobility scenarios, the conventional OFDM suffers from severe Doppler spread and thereby serious inter-carrier interference (ICI). Recently, a novel two-dimensional modulation, i.e., orthogonal time frequency space (OTFS), has been regarded as a promising alternative to the OFDM [15]. Different from the OFDM in the time-frequency domain, the OTFS modulation works in the delay-Doppler (DD) domain. Thus, when considering the OTFS-based DFRC systems, the HBF design may face the challenges. For example, how to achieve appropriate radar and communication objective functions based on OTFS modulation signaling with the HBF structure? Moreover, for the HBF in OTFS-based DFRC systems, the digital beamforming is designed for each DD block, while the analog beamforming needs to be optimized for the whole bandwidth. The corresponding problem has a stronger coupling between the analog and digital beamformers. Additionally, since the number of DD blocks are very large, it is of utmost necessity to seek a low-complexity solution. In summary, it is of great interest to examine performance of the OTFS-based DFRC systems with the HBF structure for future works.

VI. CONCLUSION

Hybrid beamforming aided DFRC has the potential to significantly improve the energy/spectral efficiency and enable ubiquitous connectivity in future 5G and 6G networks. In order to imperatively understand and tackle the challenges associated with it, this article presented a comprehensive overview of DFRC with hybrid beamforming technology. Starting from the fundamentals of the hybrid beamforming, we first introduced the system model of the DFRC with hybrid beamforming, including the system structure and DFRC transceiver architecture. Then the design principles for hybrid beamforming incorporating DFRC system was introduced based on performance metrics and prevalent approaches. We then present representative results to highlight the principles and finally outline several future research directions that can facilitate the full potential of DFRC with hybrid beamforming technology.

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