Distributed Dual-Function Radar-Communication MIMO System with Optimized Resource Allocation

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***Abstract*—In this paper, we propose a novel distributed dual-function radar-communication (DFRC) MIMO system capable of simultaneously performing radar and communication tasks. The radar objective is to achieve the desired target localization performance whereas the communication objective is to optimize the overall data rate. The distributed DFRC MIMO system performs both objectives by optimizing the power allocation of the different transmitters in the DFRC system. A dictionary of radar waveforms is used at each transmitter and the communication information is embedded in the radar waveform by exploiting waveform diversity. The proposed strategy can serve multiple communication receivers located in the vicinity of the distributed DFRC MIMO system. Simulation results illustrate the performance of the proposed strategy.**

Keywords: Distributed MIMO radar, dual-function radar-communication, power allocation, target localization.

I. Introduction

In the past decade, the issue of spectrum sharing has attracted significant attention due to the increasing congestion of spectral resources [1–4]. Modern wireless communication systems demand the expansion of existing spectral allocations to improve the data rate. In addition, emerging technical innovations, like Internet-of-Things, require new frequency allocations [5]. In this context, great efforts have been made in the field of cognitive radios to efficiently manage the spectral utilization [6]. Recently, co-existence of multiple applications within the same frequency bands has been proposed to mollify the spectral congestion by simultaneously sharing the same spectral resources [7–11]. Dual-function radar-communications (DFRC) is an important example of such platforms which performs the secondary communication operation in addition to the primary radar function while utilizing the same frequency resources [12–22].

In DFRC systems, the transmitted waveform serves both radar and communication functions. The radar operation is considered to be the principal objective of the DFRC system whereas the communication operation is assumed to be the secondary objective. Recent DFRC techniques can be broadly classified into two main categories. The first category comprises waveform diversity-based methods which exploit a dictionary of waveforms capable of performing the radar operation. The communication operation is enabled by selecting the suitable waveform from the waveform dictionary [7, 12, 21]. The second class employs beamforming-based spatial multiplexing techniques in addition to waveform diversity to achieve DFRC operation [14–20, 22].

Multiple-input multiple-output (MIMO) radar systems with widely distributed antennas are known to offer improved localization capabilities due to enhanced spatial spread [23]. The localization performance of distributed MIMO radars can be further improved by either increasing the number of participating radars or the transmitted energy. Many cases of distributed MIMO radar systems designed to improve the localization accuracy focus on Cramer-Rao bound (CRB)-based resource-aware schemes [24–26]. Resource-aware designs are very important for the deployment of sensor nodes in the network in order to reduce the operational cost. In order to enhance the performance of these systems, the participating radars are usually connected with ground stations, fusion centers, or in a distributed fashion using wireless links. Therefore, modern distributed radars need to perform the radar and communication functions simultaneously while considering the on-site resource constraints. However, DFRC approaches have not been adequately addressed for the case of distributed MIMO radar architectures.

In this paper, we propose a novel resource-aware DFRC strategy for distributed MIMO radars. We discuss the optimal power allocation for the distributed DFRC MIMO system to achieve the desired target localization and wireless communication performance. The localization accuracy is addressed in terms of the CRB whereas the communication performance is measured in terms of the optimal Shannon's capacity. Simulation results present the optimal power allocation for each transmitter in the distributed DFRC MIMO system.

We use lower-case and upper-case bold letters to represent vectors and matrices, respectively. In particular, $\mathbf{1}_{1\times M}$ stands for the $1\times M$ row vector of all ones, $\mathbf{I}_{M\times M}$ denotes the $M\times M$ identity matrix. The superscripts $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{*}$ represent the transpose and complex conjugate, respectively. $|\cdot|_2$ stands for the l_2-norm of a vector.

II. System Model

A. Radar sub-system

Consider a narrowband distributed MIMO radar system consisting of M transmitters and N receivers, which are arbitrarily located in a two-dimensional (2-D) coordinate system at the locations (x_m, y_m) and (x_n, y_n), respectively, for

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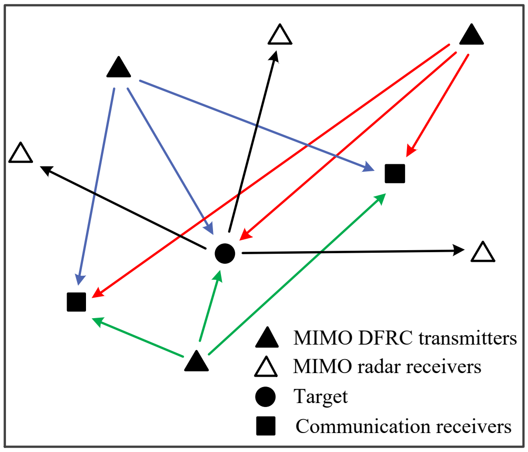

Fig. 1. Distributed DRFC MIMO system.

$1 \leq m \leq M$ and $1 \leq n \leq N$. Assume a point target located at (x, y). The radar acts as a distributed DFRC MIMO system whose primary objective is to track the target location. A coarse estimate of the parameters related to the target's radar cross-section (RCS) and position is assumed available from the previous cycles. During each radar pulse, each transmitter radiates a unit-power orthogonal waveform $s_m(t)$, such that $(1/T)\int_0^T |s_m(t)|^2 dt = 1$ and $(1/T)\int_0^T s_m(t)s_n^*(t)dt = 0$ for $m \neq n$, where T is the duration of each pulse and t is the fast time. Fig. 1 illustrates the DFRC MIMO system.

The radar signal corresponding to the m-th transmitter and the n-th receiver is expressed as:

$$s_{m,n}(t) = \sqrt{\alpha_{m,n} p_{m_{\rm tx}}} h_{m,n} s_m(t - \tau_{m,n}) + w_{m,n}(t), \quad (1)$$

where $\alpha_{m,n}$ represents the signal variation due to path loss effects, $p_{m_{\rm tx}}$ is the transmit power of signal $s_m(t)$ emitted from the m-th transmitter, $h_{m,n}$ denotes the target RCS for the propagation path from the m-th transmitter to the n-th receiver, and $w_{m,n}(t) \sim \mathcal{CN}(0, \sigma_w^2)$ represents the circularly symmetric zero-mean complex white Gaussian noise. The propagation delay $\tau_{m,n}$ due to the propagation path from the m-th transmitter to the n-th receiver is denoted as $\tau_{m,n} = (D_{m\rm tx} + D_{n\rm rx})/c$, where $D_{m\rm tx}$ and $D_{n\rm rx}$ are the range to target from the m-th transmitter and that from the n-th receiver, respectively, and c is the propagation velocity of the transmitted signals. The path loss factor takes the form of $\alpha_{m,n} \propto D_{m_{\rm tx}}^{-2} D_{n_{\rm rx}}^{-2}$. Moreover, let $\mathbf{h} = [h_{1,1}, h_{1,2}, \ldots, h_{M,1}, h_{2,1}, \ldots, h_{M,N}]^{\rm T}$ be the $MN \times 1$ vector of all bi-static RCS of the targets, and $\mathbf{p}_{\rm tx} = [p_{1_{\rm tx}}, p_{2_{\rm tx}}, \ldots, p_{M_{\rm tx}}]^{\rm T}$ be the $M \times 1$ vector containing all the transmit powers from all transmitters of the DFRC system. In addition, $\mathbf{p}_{\rm tx,max} = [p_{1_{\rm tx,max}}, p_{2_{\rm tx,max}}, \ldots, p_{M_{\rm tx,max}}]^{\rm T}$ and $\mathbf{p}_{\rm tx,min} = [p_{1_{\rm tx,min}}, p_{2_{\rm tx,min}}, \ldots, p_{M_{\rm tx,min}}]^{\rm T}$ are the $M \times 1$ vectors respectively representing the maximum and the minimum allowable transmit power from the M transmitters. We further denote $P_{{\rm total}_{\max}} \leq \sum_{m=1}^{M} p_{m_{\rm tx,max}}$ as the maximum allowable power to be transmitted from the DFRC transmitters collectively.

The radar performance can be evaluated in terms of the CRB representing the lower bound on the mean squared error of the target's location estimates, expressed as [24–26]:

$$\sigma_{x,y}(\mathbf{p}_{\rm tx}) = \frac{\mathbf{q}^{\rm T}\mathbf{p}_{\rm tx}}{\mathbf{p}_{\rm tx}^{\rm T}\mathbf{A}\mathbf{p}_{\rm tx}}, \quad (2)$$

where $\mathbf{q} = \mathbf{q}_a + \mathbf{q}_b$, $\mathbf{A} = \mathbf{q}_a\mathbf{q}_b^{\rm T} - \mathbf{q}_c\mathbf{q}_c^{\rm T}$, $\mathbf{q}_a = [q_{a_1}, q_{a_2}, \ldots, q_{a_M}]^{\rm T}$, $\mathbf{q}_b = [q_{b_1}, q_{b_2}, \ldots, q_{b_M}]^{\rm T}$ and $\mathbf{q}_c = [q_{c_1}, q_{c_2}, \ldots, q_{c_M}]^{\rm T}$. Here,

$$\begin{aligned}
q_{a_m} &= \xi_m \sum_{n=1}^{N} \alpha_{m,n}|h_{m,n}|^2 \left(\frac{x_m - x}{D_{m_{\rm tx}}} + \frac{x_n - x}{D_{n_{\rm rx}}}\right)^2, \\
q_{b_m} &= \xi_m \sum_{n=1}^{N} \alpha_{m,n}|h_{m,n}|^2 \left(\frac{y_m - x}{D_{m_{\rm tx}}} + \frac{y_n - x}{D_{n_{\rm rx}}}\right)^2, \\
q_{c_m} &= \xi_m \sum_{n=1}^{N} \alpha_{m,n}|h_{m,n}|^2 \left(\frac{x_m - x}{D_{m_{\rm tx}}} + \frac{x_n - x}{D_{n_{\rm rx}}}\right)\left(\frac{y_m - x}{D_{m_{\rm tx}}} + \frac{y_n - x}{D_{n_{\rm rx}}}\right),
\end{aligned} \quad (3)$$

where $\xi_m = 8\pi^2\mathcal{B}_m^2/(\sigma_w^2 c^2)$, and $\mathcal{B}_m$ is the effective bandwidth of the signal transmitted from the m-th transmitter.

B. Communication sub-system

Consider R communication receivers that are located in the vicinity of the distributed DFRC MIMO system. Assume that the signals reflected from the radar target and received at each communication receiver have a significantly lower magnitude compared to the line-of-sight transmission from the transmitters and, thus, are ignored. Then, we can express the received signal at the r-th ($1 \leq r \leq R$) receiver as:

$$s_{m,r}(t) = \sqrt{\beta_{m,r} p_{m_{\rm tx}}} g_{m,r} s_m(t - \kappa_{m,r}) + w_{m,r}(t), \quad (4)$$

where $g_{m,r}$ denotes the complex channel gain, $\kappa_{m,r}$ is the propagation delay, and $\beta_{m,r} \propto \mathcal{D}_{m,r}^{-2}$ incorporates the path loss effects, and $\mathcal{D}_{m,r}$ is the distance between the m-th transmitter and the r-th communication receiver. We assume $w_{m,r}(t) \sim \mathcal{CN}(0, \sigma_{m,r})$ be circularly complex white Gaussian noise whose statistics are known at the transmitter. The channel state information, expressed as the complex channel gain vector $\mathbf{g} = [g_{1,1}, g_{1,2}, \ldots, g_{M,1}, \ldots, g_{M,R}]^{\rm T}$, is also assumed to be known at the radar fusion center.

The communication performance is evaluated in terms of the achieved Shannon's capacity. The data rate from the m-th transmitter to the r-th receiver is expressed in terms of Shannon's capacity as:

$$\Re_{m,r} = \log_2\left(1 + \frac{|g_{m,r}|^2 p_{m_{\rm tx}}}{\Gamma_{m,r}\sigma_{m,r}^2}\right) = \log_2\left(1 + \frac{p_{m,\rm tx}}{\gamma_{m,r}}\right), \quad (5)$$

where $\Gamma_{m,r} \geq 1$ represents the signal-to-noise ratio (SNR) gap which translates the loss in the data rate into the loss in the SNR and is determined by the coding scheme, and $\gamma_{m,r} = \Gamma_{m,r}\sigma_{m,r}^2/|g_{m,r}|^2$. The sum data rate per radar pulse can be calculated as $\Re = \sum_{m=1}^{M}\sum_{r=1}^{R}\Re_{m,r}$.

III. Optimal Power Allocation for Distributed DFRC MIMO System

A. Radar-only operation

The optimal power allocation for radar-only operation is derived in [25] as:

$$\begin{aligned}
&\text{minimize} && \mathbf{1}_{1\times M}\mathbf{p}_{\rm tx} \\
&\text{subject to} && \mathbf{p}_{\rm tx,min} \leq \mathbf{p}_{\rm tx} \leq \mathbf{p}_{\rm tx,max}, \\
& && \sigma_{x,y}(\mathbf{p}_{\rm tx}) = \eta.
\end{aligned} \quad (6)$$

The optimization in (6) minimizes the total transmit power for the distributed MIMO radar such that a desirable localization accuracy, described in terms of the CRB η, is achieved. The optimization problem (6) can be relaxed to the following convex form [25]:

$$\begin{array}{ll} \text{minimize} & \mathbf{1}_{1\times M}\mathbf{p}_{\mathrm{tx}} \\ \text{subject to} & \mathbf{p}_{\mathrm{tx,min}} \leq \mathbf{p}_{\mathrm{tx}} \leq \mathbf{p}_{\mathrm{tx,max}}, \\ & \mathbf{q} - \eta \mathbf{A}\mathbf{p}_{\mathrm{tx}} \leq \mathbf{0}. \end{array} \tag{7}$$

The solution of the convex optimization problem (7) yields the optimized transmit power vector $\mathbf{p}_{\mathrm{tx,opt}}$, which can be used as a starting point for a local optimization applied to the original optimization (6).

B. Communication-only operation

We assume that the waveform transmitted from each transmitter is broadcast to all communication users located in the vicinity of the DFRC transmitters. We assume that the channel side information is known at the DFRC transmitter and communication receivers. Therefore, we optimize the power allocation by exploiting the conventional water-filling approach [27]. The optimal power allocation for the maximum allowable transmit power is achieved by solving the following equation simultaneously for all the communication receivers ($1 \leq r \leq R$):

$$\mathbf{U}\begin{bmatrix} \mathbf{p}_{\mathrm{tx}} \\ X_r \end{bmatrix} = \begin{bmatrix} P_{\mathrm{total_{max}}} \\ \boldsymbol{\gamma}_r \end{bmatrix}, \tag{8}$$

where

$$\mathbf{U} = \begin{bmatrix} \mathbf{1}_{1\times M} & 0 \\ \mathbf{I}_{M\times M} & -\mathbf{1}^{\mathrm{T}}_{1\times M} \end{bmatrix}, \quad \boldsymbol{\gamma}_r = -\begin{bmatrix} \gamma_{1,r} \\ \gamma_{2,r} \\ \vdots \\ \gamma_{M,r} \end{bmatrix},$$

where X_r represents the water-filling power level. Eq. (8) may provide different optimal power distributions for different communication users depending on their channel side information. Moreover, the solution of Eq. (8) can also provide negative power if any channel has a deep fade. Therefore, we can write Eq. (8) for all the communication receivers as the following constrained least-square optimization problem:

$$\begin{array}{ll} \text{minimize} & \displaystyle\sum_{r=1}^{R}\left|\mathbf{V}\begin{bmatrix} \mathbf{p}_{\mathrm{tx}} \\ X_r \end{bmatrix} - \boldsymbol{\gamma}_r\right|_2 \\ \text{subject to} & \mathbf{p}_{\mathrm{tx,min}} \leq \mathbf{p}_{\mathrm{tx}} \leq \mathbf{p}_{\mathrm{tx,max}}, \\ & \mathbf{1}^{\mathrm{T}}\mathbf{p}_{\mathrm{tx}} \leq P_{\mathrm{total_{max}}}, \\ & X_r \geq 0, \quad r = 1, 2, \ldots, R, \end{array} \tag{9}$$

where $\mathbf{V} = \begin{bmatrix} \mathbf{I}_{M\times M} & -\mathbf{1}^{\mathrm{T}}_{1\times M} \end{bmatrix}$. The optimization problem (9) is convex. However, unlike (6) and (7) where the least power required for satisfactory radar operation is extracted, it utilizes the maximum allowable power and distributes it with respect to channel quality for all the communication users. For a given maximum power $P_{\mathrm{total_{max}}}$, the optimization problem (9) tends to maximize the water-filling level X_r, thus resulting in best the data rate for the best channel conditions.

C. Dual-function radar-communication

The optimal power allocation extracted from the optimization problems (7) and (9), respectively designed for radar-only and communication-only operations, are not favorable for the acceptable joint operation DFRC system. The power allocation from optimization (7) provides the minimal required power from all the transmitters of the distributed radar. As such, this scheme may not establish an acceptable communication data rate as most of the transmitters work on a low power in ideal radar conditions, resulting in unacceptable SNR and data rate for communication users. Moreover, the resulting power from the optimization problem (7) is independent of the communication channel side information. Likewise, the resource allocation from the optimization problem (9) is not suitable for radar operation as the power distribution for this case is independent of the radar performance and may result in unacceptable target tracking performance, even after the maximum allowable power is utilized.

We can add the radar performance constraint in the optimization problem (9) to obtain the following modified convex optimization problem:

$$\begin{array}{ll} \text{minimize} & \displaystyle\sum_{r=1}^{R}\left|\mathbf{V}\begin{bmatrix} \mathbf{p}_{\mathrm{tx}} \\ X_r \end{bmatrix} - \boldsymbol{\gamma}_r\right|_2 \\ \text{subject to} & \mathbf{p}_{\mathrm{tx,min}} \leq \mathbf{p}_{\mathrm{tx}} \leq \mathbf{p}_{\mathrm{tx,max}}, \\ & \mathbf{q} - \eta\mathbf{A}\mathbf{p}_{\mathrm{tx}} \leq \mathbf{0}, \\ & \mathbf{1}^{\mathrm{T}}\mathbf{p}_{\mathrm{tx}} \leq P_{\mathrm{total_{max}}}, \\ & X_r \geq 0, \quad r = 1, 2, \ldots, R. \end{array} \tag{10}$$

The optimization problem (10) provides the optimal power allocation for distributed DFRC transmitters under the maximum allowable power constraint such that the localization error for the radar operation is bounded by η. At the same time, our objective function tends to maximize the water-filling level X_r to improve the communication data rate.

IV. Information Embedding

The information embedding can be accomplished by utilizing waveform diversity. If each transmitter is assigned a dictionary of K radar waveforms, the total bits transmitted from the distributed DFRC MIMO system during one radar pulse is $M \log_2 K$, provided that the dictionaries are non-overlapping and all transmitters are active.

The signal received at the communication receiver r can be expressed as:

$$\begin{aligned} s_r(t) &= \sum_{m=1}^{M} s_{m,r}(t) \\ &= \sum_{m=1}^{M} \sqrt{\beta_{m,r} p_{m_{\mathrm{tx}}}}\, g_{m,r} s_m(t-\kappa_{m,r}) + w_r(t), \end{aligned} \tag{11}$$

where $w_r(t) = \sum_{m=1}^{M} w_{m,r}(t)$. Matched filtering can be exploited at the communication receivers to synthesize the embedded information by feeding the time delayed versions

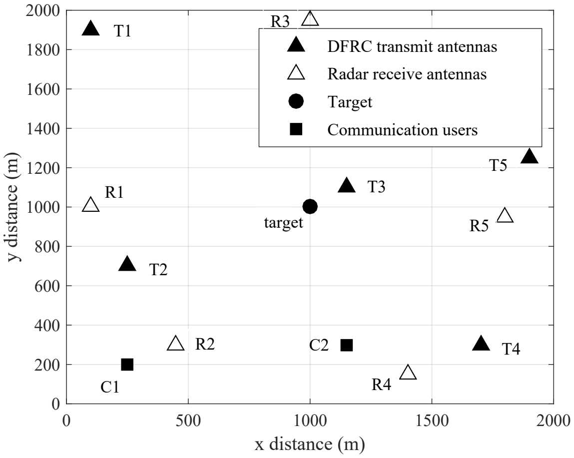

Fig. 2. Simulation layout for distributed DFRC MIMO system.

of $s_r(t)$ in the matched filter as follows:

$$y_r(k) = \frac{1}{T}\int_0^T s_r(t + k\Delta t) s_m^*(t) dt \\ = \begin{cases} \sqrt{\beta_{m,r} p_{m_{\mathrm{tx}}}} g_{m,r} + w_{r,k}(t), & \text{if } s_m(t) \text{ transmitted}, \\ w_{r,k}(t), & \text{otherwise}, \end{cases} \tag{12}$$

where Δt is the time delay defining the time resolution of delay matched filtering, k is a non-negative integer with $0 \leq k \leq T/\Delta t$ and $w_{r,k}(t)$ is the noise output.

V. Simulation Results

Consider a distributed DFRC MIMO system consisting of $M = 5$ isotropic transmitters located at $(100, 1900)$ m, $(250, 700)$ m, $(1150, 1100)$ m, $(1700, 300)$ m and $(1900, 1250)$ m, respectively, in the two-dimensional space. The radar uses $N = 5$ receive antennas located at $(100, 1000)$ m, $(450, 300)$ m, $(1000, 1950)$ m, $(1400, 150)$ m and $(1800, 950)$ m, respectively. A point target is located at the coordinate of $(1000, 1000)$ m. Two communication receivers are located at $(250, 200)$ m and $(1150, 300)$ m, respectively. Fig. 2 shows the arrangement of the distributed DFRC MIMO system and the communication receivers in the two-dimensional coordinate system. Each transmitter can transmit a maximum of 100 W power during each radar pulse whereas the minimum allowed power for each transmitter is 1 W. Moreover, the maximum total allowable transmit power from the distributed DFRC MIMO system, $P_{\mathrm{total}_{\max}}$, is 400 W. The data rate for the communication system is calculated in terms of Shannon's capacity.

The magnitude of all elements of the RCS vector $\mathbf{h}$ is assumed to be uniformly distributed between 0.9 to 1. For this simulation, we took the magnitude of $\mathbf{h}$ as $[0.962, 0.912, 0.969, 0.977, 0.907, 0.918, 0.945, 0.952, 0.982, 0.957, 0.946, 0.945, 0.952, 0.982, 0.957, 0.964, 0.941, 0.915, 0.956, 0.909, 0.906, 0.979, 0.980, 0.996, 0.902]^{\mathrm{T}}$ whereas their phases independently follow the uniform distribution. The path loss coefficients $\alpha_{m,n}$ and $\beta_{m,r}$ are calculated using the location coordinates of the distributed DFRC MIMO system, the communication receivers, and the target, whereas $\xi_m = 8.773 \times 10^5$ is assumed for all $1 \leq m \leq M$. For the communication purpose, we considered $\boldsymbol{\gamma}_1 = -[1/0.8,\ 1/1,\ 1/0.01,\ 1/0.9,\ 1/0.95]^{\mathrm{T}}$ and $\boldsymbol{\gamma}_2 = -[1/0.6, 1/0.9, 1/0.01, 1/0.85, 1/0.73]^{\mathrm{T}}$. In this case, both communication receivers experience deep fading with the third transmitter of the distributed DFRC MIMO system. On the other hand, the path loss coefficients $\alpha_{m,n}$ are the highest for the third transmitter of the DFRC system because of its proximity with the target. This implies that the third transmitter is the most important in determining the target localization. However, it is the least important for optimizing the data rate for the communication system due to the smallest communication SNR (deep fading) with both communication receivers.

TABLE I. Power allocation for proposed DFRC system for $M = N = 5$ and $R = 2$, $P_{\mathrm{total}_{\max}} = 400$ W, $\eta_{\mathrm{desired}} = 10$ m^2

	Radar-only (7)	Communication-only (9)	DFRC (10)
$\mathbf{p}_{\mathrm{tx}}$ (W)	$\begin{bmatrix} 1.0 \\ 1.0 \\ 90.46 \\ 1.0 \\ 1.0 \end{bmatrix}$	$\begin{bmatrix} 99.45 \\ 99.95 \\ 1.02 \\ 99.86 \\ 99.72 \end{bmatrix}$	$\begin{bmatrix} 89.39 \\ 81.27 \\ 72.22 \\ 79.43 \\ 77.69 \end{bmatrix}$
P_{total} (W)	94.46	400	400
η (m^2)	9.97	30.59	8.21
$\Re$ (bits/pulse)	8.87	51.16	50.44

Table I summarizes the power allocation results and the radar as well as communication performance for the optimization strategies of the radar-only case [25], the communication-only case, and the proposed DFRC case. The desired radar performance is the mean squared localization error of $\eta_{\mathrm{desired}} = 10$ m^2. The radar-only optimization scheme described in (7) provides the optimal power required for the acceptable operation of radar. It allocates most of the transmit power to the third transmitter because it provides the best target localization accuracy due to its lowest path loss coefficient. However, the third transmitter has poor communication channel conditions, thus making it unsuitable for joint radar-communication operation because the yielding communication sum data rate is only 8.87 bits/pulse. The communication-only scheme (9) exploits water-filling under the available power constraint to achieve the optimal sum data rate of 51.16 bits/pulse. It can be observed that the least power is allocated to the third transmitter due to its worst communication conditions and more power is allocated to other transmitters with better communication channel conditions. Although this scheme is the best to achieve the optimal data rate, it results in a high CRB of $\eta = 30.59$ m^2 while using 400 W power, thus failing to achieve the desired radar performance, even consuming the maximum allowable total power.

The distributed DFRC MIMO scheme described in (10) allocates the optimal power to different transmitters by simultaneously considering the communication and radar objectives. As the radar objective is the primary one, it is observed that the DFRC scheme allocates a considerable amount of power to the third transmitter, resulting in the desired target localization accuracy with $\eta = 8.21$ m^2, whereas the secondary communication operation achieves a sum data rate of 50.44 bits/pulse. The results clearly confirm the promising performance of the proposed strategy.

VI. Conclusion

In this paper, we proposed a distributed DFRC MIMO system which optimizes the power allocation for a desired localization accuracy of the radar and improves the communication data rate by considering the channel side information. The power allocation was derived for the maximum allowable total power of the DFRC transmitters ensuring the desired radar-communication performance. Simulation results verify the effectiveness of the proposed scheme.

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