Beam Synthesis under Feasible Scenarios for Radar and Communications Combined Systems

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***Abstract*—Spectrum sharing for radar and communications can maximize the utilization of frequency resource. Though several studies have considered the coexistence and joint transmission to accomplish the missions of radar target detection and wireless communications simultaneously, none of the previous studies have considered feasible scenarios. In this paper, we consider a feasible scenario under which all the multiple antennas at the base station are used for joint transmission of radar beams and communications signals. With a careful consideration of the channel models, a beam synthesis algorithm is reviewed for the shared antenna utilization for both radar and communications. Numerical evaluation is provided to investigate the trade-off between the radar and communications performance.**

***Index Terms*—Radar and communication combined systems, beam synthesis, directional channel model**

I. Introduction

Recently, frequency spectrum sharing for radar and communications has attracted reserch interest because of its high potential achieving maximized utilization of frequency resource and reducing the implementation cost [1], [2]. In radar systems, phased array or multi-input multi-output (MIMO) radar techniques require the employment of multiple antennas and careful beamforming optimization. In addition, multi-antenna joint transmission techniques have been extensively studied in multi-user communication networks. To accomplish the mission of joint transmission for both radar and communications, a few studies have been conducted. In particular, a waveform design framework was proposed in [3] for the coexistence of MIMO radar and communications in the same system. In [1], the beam synthesis was studied for the separated antenna deployment and shared antenna deployment. In this paper, we restrict ourselves to the shared antenna deployment scenario, where all the antennas at the base station are used both for the transmission of radar and communications signals. However, none of the previous studies have carefully considered the scenarios and channel models.

In this paper, we revisit the ray-based channel model and the beam synthesis algorithm for the shared deployment case. In particular, angular locations of the users and the range of the target presence are carefully assumed to consider a feasible scenario. We then model the channels based on [4]–[6]. New observations are discussed in the viewpoint of the trade-off between the data rate and peak-to-sidelobe ratio (PSL).

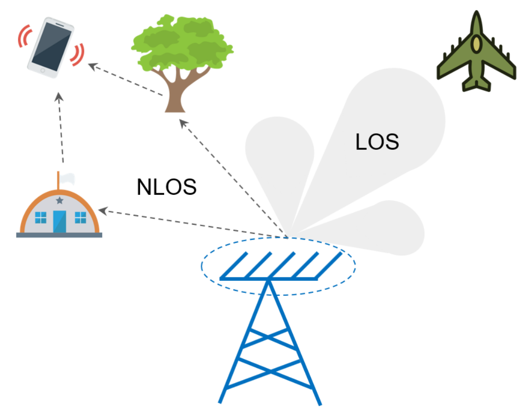

Fig. 1: Antenna shared deployment for the collocated radar and communication BS. In case of radar, there is the target in LOS, on the other hands, there is no direct way, i.e. NLOS situaion for UEs.

II. System Model

We consider a radar and communications combined system, which can simultaneously transmit signals to a target that can be detected by radar and communication symbols to downlink users. As shown in Fig. 1, the radar signal and communication signals are transmitted from the base station (BS) simultaneously. It is assumed that the target exists on line-of-sight (LOS), while user equipment (UE) exists on Non-line-of-sight (NLOS). Uniform linear array (ULA) is employed with N antenna elements.

From the above model, the received signal of the i-th user is given as

$$y_i[l] = \mathbf{h}_i^T \sum_{k=1}^{K} \mathbf{t}_k d_k[l] + n_i[l], \forall i, \tag{1}$$

where $\mathbf{h}_i$ is the channel vectors between the antenna and the i-th user, $\mathbf{t}_i \in \mathbb{C}^{N\times 1}$ and $d_k[l]$ denote the beamforming vector and the communication symbol, respectively, and $n_i[l] \sim \mathcal{CN}(0, N_0)$ stands for the received noise of the i-th user. Here, K is the number of all users.

Letting $\mathbf{T}_i = \mathbf{t}_i\mathbf{t}_i^H$, the received SINR of the i-th user is

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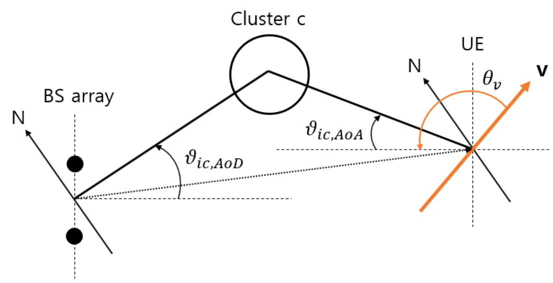

Fig. 2: Channel parameter description between BS array and UE. $\vartheta_{ic,AoD}$ stands for the angle of departure (AoD), $\vartheta_{ic,AoA}$ means the angle of arrivals, and θ_v is the angle of the velocity vector with respect to the MS.

given by

$$\gamma_i = \frac{\left|\mathbf{h}_i^T \mathbf{t}_i\right|^2}{\sum_{\substack{k=1\\k\neq i}}^{K}\left|\mathbf{h}_i^T \mathbf{t}_k\right|^2 + N_0} = \frac{\text{tr }\left(\mathbf{h}_i^* \mathbf{h}_i^T \mathbf{T}_i\right)}{\text{tr}\left(\mathbf{h}_i^* \mathbf{h}_i^T \sum_{\substack{k=1\\k\neq i}}^{K} \mathbf{T}_k\right) + N_0}. \quad (2)$$

As noted in [1], the followings are standard assumptions on the radar and communication channels:

1) The communication signals are statistically independent of the radar signals;
2) The channel between the antenna and the user is flat Rayleigh fading.

III. Channel model

In this section, unlike other previous studies, the channel model is presented to check the feasibility of the system model. From [6], the propagation environment is well characterized by a clustered channel model. The channel of i-th user is given by

$$\mathbf{h}_i = \sqrt{N}\sum_{c=1}^{C} \rho_{ic}\mathbf{a}_t^H(\vartheta_{ic}), \quad (3)$$

where C is the number of cluster. Since it is assumed that the joint channel is the flat Rayleigh fading, $|\rho_{ic}|$ follows Rayleigh fading for each link. In addition, $\mathbf{a}_t^H(\vartheta_{ic})$ stands for the steering vector of the transmit antenna. From ULAs, the steering vector can be specified by $\mathbf{a}_t^H(\vartheta_{ic}) = [1, e^{j2\pi\Delta \sin\vartheta_{ic}}, ..., e^{j2\pi(N_t-1)\Delta\sin\vartheta_{ic}}]^T \in \mathbb{C}^{N_t\times 1}$. The distance between adjacent antenna elements is denoted by Δ, which is generally assumed by half of wavelength.

IV. Beam Synthesis Algorithm

The beam synthesis algorithm proposed in [1] is reviewed for self-completeness. The beam synthesis problem can be formulated as

$$\begin{aligned}
\underset{\alpha,\mathbf{R}}{\text{minimize}} \quad & t \\
\text{subject to} \quad & \sum_{m=1}^{M}\left|\alpha\tilde{P}_d(\theta_m) - \mathbf{a}^H(\theta_m)\mathbf{R}\mathbf{a}(\theta_m)\right|^2 \le t, \\
& \text{diag}(\mathbf{R}) = \frac{P_0\mathbf{1}}{N}, \\
& \mathbf{R}\succeq 0, \mathbf{R} = \mathbf{R}^H, \\
& \alpha \ge 0, \\
& t \ge 0,
\end{aligned} \quad (4)$$

where $\{\theta_m\}_{m=1}^M$ is the detection angle that covers angle range of $[-\pi/2, \pi/2]$, $\tilde{P}_d(\theta_m)$ is the desired beampattern that we want to implement at our joint radar and communication system, and P_0 is the power budget, and $\mathbf{1} = [1, 1, ..., 1]^T \in \mathbb{R}^{N\times 1}$.

Finally, by the waveform covariance matrix, which is denoted by $\mathbf{R}$, we can design our shared deployment beamforming vector from

$$\underset{\mathbf{T}_i}{\text{minimize}} \quad t \quad (5a)$$

$$\text{subject to} \quad \left\|\sum_{i=1}^{K}\mathbf{T}_i - \alpha\mathbf{R}\right\|_F^2 \le t, \quad (5b)$$

$$\text{diag}\left(\sum_{i=1}^{K}\mathbf{T}_i\right) = \frac{P_0\mathbf{1}}{N}, \quad (5c)$$

$$\alpha \ge 0, \quad (5d)$$

$$\mathbf{T}_i \succeq 0, \mathbf{T}_i = \mathbf{T}_i^H, \text{rank}(\mathbf{T}_i) = 1, \forall i, \quad (5e)$$

$$\gamma_i \ge \Gamma_i, \forall i, \quad (5f)$$

where $\mathbf{R}$ is obtained by (4), Γ_i is the allocated SINR for i-th user, $\mathbf{1} = [1, 1, ..., 1]^T \in \mathbb{R}^{N\times 1}$, and N is the number of shared antenna. Unlike in [1], we introduce the scaling factor α in (5b), which leads to more chances to obtain feasible solutions.

After omitting the rank-1 constraint term, we can solve the problem and obtain suboptimal minimum value t from rank-1 approximation.

V. Numerical Results

In this section, numerical results under the considered channel model are provided. Figures 3 and 4 show the beam patterns with the considered directional channel model and the random channel model, respectively, where $N = 20$, SNR=20dB, Γ_i =21dB, $K = 1$, and the LOS angle is between $-\pi/6$ and $\pi/6$. As shown in Fig. 3, in the directional channel model, some angular directions where the users are located should have relatively high array gain to satisfy the minimum SINR consrtaint. As a result, the overall beam pattern is worse than with the simple random channel model case in Fig. 4. That is, beam pattern may be worse in the considered feasible environment.

Figures 5 and 6 show the beam pattern with the directional and random channel models, respectively, where $N = 20$,

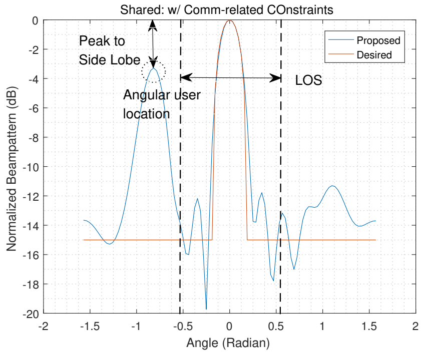

Fig. 3: Beam pattern with the directional channel model where $N = 20$, SNR=20dB, Γ_i =21dB, $K = 1$, and the LOS angle is between $-\pi/6$ and $\pi/6$.

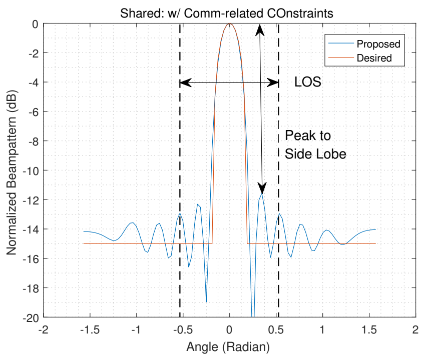

Fig. 4: Beam pattern with the random channel model where $N = 20$, SNR=20dB, Γ_i =21dB, $K = 1$, and the LOS angle is between $-\pi/6$ and $\pi/6$.

SNR=20dB, Γ_i =21dB, $K = 2$, and the LOS angle is between $-\pi/6$ and $\pi/6$. Compared to the results in Figs. 3 and 4, the sidelobe level is higher because of more users, i.e., $K = 2$, yielding more constraints of the minimum SINR.

Desired SINRs	Obtained minimum SINRs	PSL value
16.99	16.99	15.43
20.0	20.0	11.58
21.76	21.76	10.14
23.01	23.01	11.27
23.98	23.98	8.96
24.77	24.77	6.2
25.44	25.44	9.12
26.02	26.02	4.92
26.5	26.53	5.92
26.99	26.99	6.87

TABLE I: Desired SINRs, obtained minimum SINRs and PSL values in dB scale where $N = 20$, $K = 2$, the LOS angle is between $-\pi/6$ and $\pi/6$, and Γ_i is varied from 17dB to 27dB.

Table I shows the achievable minimum SINR and peak-to-sidelobe-level (PSL) with respect to variable desired minimum SINR, i.e., Γ_i, where $N = 20$, SNR=20dB, $K = 2$, and

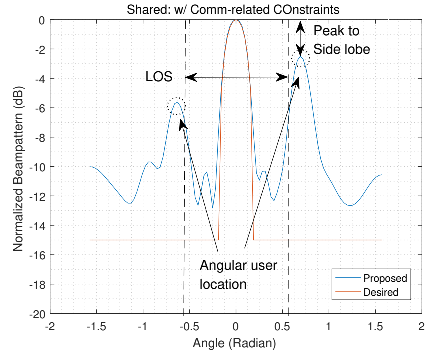

Fig. 5: Beam pattern with the directional channel model where $N = 20$, SNR=20dB, $\Gamma_i = 21$dB, $K = 2$, and the LOS angle is between $-\pi/6$ and $\pi/6$.

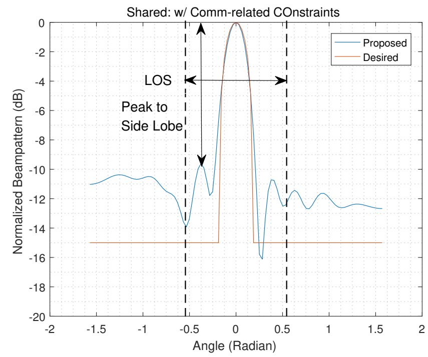

Fig. 6: Beam pattern with the random channel model where $N = 20$, SNR=20dB, $\Gamma_i = 21$dB, $K = 2$, and the LOS angle is between $-\pi/6$ and $\pi/6$.

the LOS angle is between $-\pi/6$ and $\pi/6$. A clear trade-off between the achievable minimum SINR and the PSL performance is observed from the table.

VI. Conclusion

We have proposed the directional channel model to consider a feasible scenario for the communication and radar combined system, where the communication and radar signals are simultaneously transmitted by the same antennas. The beam synthesis performance for radar turned out to be lower than in the previous studies due to the impact of the directional location of the users. In our future work, we will develop a joint transmission beam synthesis algorithm under the feasible scenario developed in this work. In addition, we shall consider a wideband channel model to expand the idea to the case of orthogonal frequency division multiplexing signaling.

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