QUANTIZED PRECODING AND RIS-ASSISTED MODULATION FOR INTEGRATED SENSING AND COMMUNICATIONS SYSTEMS

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ABSTRACT

In this paper, we present a novel reconfigurable intelligent surface (RIS)-assisted integrated sensing and communication (ISAC) system with 1-bit quantization at the ISAC base station. An RIS is introduced in the ISAC system to mitigate the effects of coarse quantization and to enable the co-existence between sensing and communication functionalities. Specifically, we design a transmit precoder to obtain 1-bit sensing waveforms having a desired radiation pattern. The RIS phase shifts are then designed to modulate the 1-bit sensing waveform to transmit M-ary phase shift keying symbols to users. Through numerical simulations, we show that the proposed method offers significantly improved symbol error probabilities when compared to MIMO communication systems having quantized linear precoders, while still offering comparable sensing performance as that of unquantized sensing systems.

Index Terms— Integrated sensing and communication, MIMO systems, quantized precoding, reconfigurable intelligent surfaces.

1. INTRODUCTION

Integrated sensing and communication (ISAC) systems, which carry out both communication and sensing functionalities by sharing hardware and spectral resources are envisioned to play an important role in the next generation of wireless systems operating at millimeter-wave frequencies [1, 2]. Realizing systems with large antenna arrays having dedicated high-resolution quantizers, i.e., digital-to-analog converters (DACs), at each antenna significantly increases the radio frequency complexity. Hence, low-resolution quantizers (e.g., 1-bit quantizers) are preferred for multiple-input multiple-output (MIMO) communication, radar, and ISAC systems [3–6]. While 1-bit sensing systems offer comparable performance to that of high resolution systems [4], the usage of coarse quantization (e.g., 1-bit DAC) at the transmitter, is found to significantly degrade the communication symbol error probability (SEP), especially at moderate to high signal-to-noise ratios (SNRs) [3].

Another major challenge in operating at mmWave frequencies is the extreme pathloss and the associated direct path blockages, which adversely affect the communication and sensing capabilities of the system. A potential solution to combat the adverse propagation environment is to use the so-called reconfigurable intelligent surfaces (RISs), which are two-dimensional arrays of passive phase shifters. These RIS phase-shifters can be remotely tuned to favorably modulate the wireless propagation environment to obtain stronger reliable links and thereby improve performance of wireless systems [7–10]. Moreover, RISs can also be used for information transmission by instantaneously adjusting the phase shifts to transmit communication symbols to the user equipments (UEs) [11, 12]. Although RISs were originally envisaged for wireless communication applications, RISs have been found to significantly improve the performance of sensing [13, 14] and ISAC systems [15–22] as well. For instance, jointly optimizing the transmit precoders and RIS phase shifts lead to improved communication and sensing performance. Existing methods on RIS-assisted ISAC systems consider ideal (i.e., infinite precision) quantization at the ISAC base station (ISAC BS) and do not account for the presence of low-resolution DACs.

In this work, we consider a multi-user multi-target RIS-assisted ISAC system with ISAC BS equipped with 1-bit DACs. We focus on the setting where the targets are directly visible to the ISAC BS, whereas the direct links to the communication users are blocked. We use RIS to achieve three objectives: (a) to enable reliable communication by introducing virtual links from ISAC BS to UEs, (b) to improve SEP at UEs by mitigating the effects of 1-bit quantization at the ISAC BS, and (c) to enable coexistence between communication and sensing functionalities. To achieve these objectives, we propose a novel scheme in which the ISAC BS transmits 1-bit quantized sensing waveforms without any communication information. The 1-bit sensing waveform is then modulated by an RIS having discrete phase shifts to transmit M-ary phase shift keying (M-PSK) communication symbols to the UEs. This scheme is advantageous since we can effectively mitigate the adverse effect of 1-bit quantization at the ISAC BS by directly carrying out the modulation at RIS.

We design the 1-bit transmit waveform at the ISAC BS to have a desired transmit beam pattern towards target directions of interest and the RIS. The instantaneous RIS phase shifts are then designed to modulate the 1-bit quantized sensing signal to carry information to the UEs. We propose a semi-definite programming solver to design the transmit precoder at the ISAC BS and also provide a closed-form solution for the RIS phase shifts when each user is served using time division multiplexing (TDM). Through numerical simulations, we demonstrate that the proposed method offers significantly improved SEP when compared with methods using quantized linear precoding for communication [3] along with RIS phase shifts selected to merely strengthen the wireless link. We also numerically show that RIS with discrete phase shifter having 3-4 bits resolution is sufficient to achieve the full benefits of the proposed scheme while suffering from a moderate radar performance loss of only about 1-2 dB in terms of worst-case target illumination power with respect to an unquantized sensing system.

2. SYSTEM MODEL

Consider an ISAC system for sensing $P$ targets while communicat-
The 1-bit quantized signal is expressed in terms of a diagonal matrix containing the diagonal entries of the covariance matrix (i.e., with diagonal entries normalized to 1) as

\[ R = \text{diag}(R) \]

transmit precoder and the unquantized signal as

\[ x = W z \]

and the transmit signal at the ISAC BS does not carry any useful information. The communication functionality is implemented by the RIS non-negative inputs and is piecewise constant. In the considered setting, the communication functionality is implemented by the RIS and the transmit signal at the ISAC BS does not carry any useful information intended for the user. Hence, the ISAC BS transmits 1-bit waveforms that are designed for radar sensing. Let us model the unquantized signal as \( x = W t \), where \( W \in \mathbb{C}^{M \times M} \) is the transmit precoder and \( t \) is the transmit beamformer.

The covariance matrix corresponding to the signal before quantization is given by \( R_x = \mathbb{E}[x_n x_n^H] = W W^H \). We normalize the covariance matrix (i.e., with diagonal entries normalized to 1) as \( R_x = \text{diag}^{-1/2}(R_x) \text{diag}(R_x) \text{diag}^{-1/2}(R_x) \), where \( \text{diag}(R_x) \) is the diagonal matrix containing the diagonal entries of \( R_x \). The covariance matrix of the 1-bit quantized signal \( z \), \( R_z = \mathbb{E}[z z^H] \), can be expressed in terms of \( R_x \) using the arc-sine rule [3, 23]. Let \( \cos^{-1}(\alpha) = \sin^{-1}\left(\frac{\sqrt{\alpha}}{|\alpha|}\right) \), \( \alpha \in \mathbb{C} \), denote the complex arc-sine function. Then, we have

\[ R_z = \frac{2}{\pi} \cos^{-1}\left( \frac{R_x}{\bar{x}} \right) \]

The 1-bit quantized signal \( z \) is scaled to meet the transmit power requirements. We consider an element-wise power constraint of \( \rho \triangleq P/|\mathbb{C}| \) per antenna at the ISAC BS so that the 1-bit quantized transmit signal is given by \( \bar{z} = \sqrt{\rho} z \).

The signal at the \( m \)-th target at time \( n \) is given by [cf. Fig. 1]

\[ r_{m,n} = \sqrt{\rho} \mathbf{h}^H_m z_n + w_n, \]

where \( w_n \sim \mathcal{CN}(0, \sigma^2) \) is the receiver noise and the wireless channels are as defined in Fig. 1. Henceforth, for brevity, we drop subscript \( k \) from \( y_{k,n} \) and \( h_{k,n} \) as we process each user using TDM. We also assume that all associated wireless channels are perfectly known. In practice, the BS-RIS-UE wireless channel can be estimated using [24].

We now formulate the problem of designing the transmit precoder \( W \) and the instantaneous RIS phase shifts \( \phi \).

### 3. PROBLEM FORMULATION

We now formulate the problem of designing the transmit precoder \( W \) and the instantaneous RIS phase shifts \( \phi \).

#### 3.1. Transmit precoder design

For reliable sensing, the ISAC BS should radiate power towards all target directions of interest. Moreover, sufficient power should also reach the RIS so that it can modulate \( u \), to send information to the UEs. Hence, we require a transmit beampattern where the power is radiated towards both the target directions and the RIS. To do so, we propose to design \( W \) to achieve the desired transmit beampattern.
Let us define the array response vector of the ISAC BS towards the direction \( \theta \) as \( a(\theta) = [1, e^{-j \pi \sin \theta}, \ldots, e^{-j \pi (M-1) \sin \theta}]^T \). The transmit power radiated towards direction \( \theta \) is given by \( P(\theta) = a^H(\theta) R_x a(\theta) \), where \( R_x \) is the covariance matrix of \( x_n \). Let \( d(\theta) \) be the desired beampattern corresponding to the angle \( \theta \). Consider a discrete grid of \( D \) angles \( \{\theta_i, 1 \leq i \leq D\} \). The beam-pattern mismatch error can be evaluated over \( D \) as \( L(R_x, \tau) = \frac{1}{D} \sum_{i=1}^{D} \left| J(\theta_i) - \tau d(\theta_i) \right|^2 \), where \( \tau \) is the autoscale parameter.

The transmit beampattern error, \( L(R_x, \tau) \), is determined by the quantized transmit covariance matrix \( R_x \), which in turn depends on the normalized unquantized covariance matrix \( R_x \) as in (1). To design \( W \), it is thus sufficient to design the unquantized transmit covariance matrix \( R_x \). Using (1), we can mathematically formulate unquantized transmit precoder design problem as

\[
(P1): \quad \text{minimize} \quad L(R_x, \tau) \quad \text{s. to} \quad R_x = \frac{2}{\pi} \sin^{-1}\left(\frac{R_x}{\tau}\right),
\]

where (3a) is due to the arc-sine law and (3b) is due to the fact that \( R_x \) is normalized. Due to the presence of the arc-sine constraint (3a), \( (P1) \) is non-convex and is difficult to solve. In the paper, we propose a convex relaxation based solver for \( (P1) \).

3.2. RIS phase shift design for modulation

With the proposed RIS-assisted modulation scheme, communication sub-system at each time instance \( n \) is a single-input single-output (SISO) system with gain \( \alpha_n \) with its SEP determined by the received SNR [25]. Hence, we propose to formulate the RIS phase shift design by choosing \( \phi_n \), so that the instantaneous SNR is maximized. We wish to re-emphasize that this design strategy is different from choosing RIS phase shifts solely based on the physical wireless channels \( H_{br} \) and \( h_{ru} \) to maximize the strength of the cascaded channel \( \text{diag}(h_{ru}^H) H_{br} \). By defining \( h_{ru} = \text{diag}(h_{ru}^H) \), we have the modified channel \( \alpha_n = \phi_n^H h_{ru} \). The instantaneous symbol detection SNR at the considered UE at time \( n \) is given by \( \gamma_n(\phi_n) = |\phi_n^H h_{ru} n|/\sigma^2 = |\sum_{i=1}^{N} \phi_n[h_{ru} n]|/\sigma^2 \). Let us recall that the instantaneous RIS phase shifts are defined as \( \omega_n = \phi_n^H h_{ru} n \) with \( |\phi_n| = 1 \) [cf. Sec. 2.3]. The instantaneous RIS phase shifts \( \phi_n \) are computed by solving

\[
(P2): \quad \phi_n^* = \arg \max_{\phi_n} \gamma_n(\phi_n) \quad \text{s. to} \quad |\phi_n| = 1, \quad \forall i.
\]

We remark that the overall RIS phase shift is \( \omega_n = \phi_n^* h_{ru} n \). Hence, discrete phase shift constraint is only for \( \omega_n \). Note that \( (P2) \) needs to be solved for each channel use or each \( n \).

To summarize, we design the transmit precoder to achieve the desired beampattern at the ISAC BS. Instantaneous RIS phase shifts \( \omega_n \) are then designed to modulate \( u_n \) with \( M \)-PSK symbols and to maximize the instantaneous received SNR at the considered UE.

4. PROPOSED SOLUTION

In this section, we develop a convex-relaxation based solver for transmit precoding. We also present a closed-form expression for the optimal solution of the instantaneous RIS phase shift \( \phi_n^* \).

4.1. Quantization-aware transmit precoder design

The major difficulty in solving \( (P1) \) is due to the non-convex constraint (3a). Instead of directly optimizing \( (P1) \) to find \( R_x \), it is sufficient to compute the optimal output transmit covariance matrix \( R_x \), since \( R_x \) can be then computed from \( R_x \) using the arc-sine law. Hence, \( (P1) \) can be equivalently written as

\[
\text{minimize} \quad R_x \quad \text{s. to} \quad L(R_x, \tau) \geq 0 \quad \text{for} \quad i,j = 1, \ldots, M, \quad R\left[R_x\right]_{i,i} \in [-1, 1],
\]

where \( (3a) \) is due to the arc-sine law and \( (3b) \) is due to the fact that \( R_x \) is normalized. Due to the presence of the arc-sine constraint (3a), \( (P1) \) is non-convex and is difficult to solve. In the paper, we propose a convex relaxation based solver for \( (P1) \).
In this section, we present numerical simulations to demonstrate performance of the proposed algorithm. Throughout the simulation, we assume two targets at $[-45^\circ, 0^\circ]$ with $M = 16$ and $N = 100$. The transmitted symbols are 64-PSK modulated and the UEs employ maximum-likelihood detectors to detect the transmitted symbol. The ISAC BS and RIS are located at $(0, 0, 0)m$, and $(50, 50, 10)m$, respectively. User locations are drawn at random from a 30$m \times 50$m rectangular region with the top-left corner at $(10, 50, 0)m$. All wireless links are modeled using a pathloss model $30 + 22 \log d$ dB with Rician distributed user links and line-of-sight target links. All SEP plots are obtained by averaging over $10^3$ independent channel realizations, each with 200 symbol transmissions. The desired transmit beampattern is selected to be a superposition of box functions of width 10 degrees centered around the target directions with a relative strength of $(1 - \beta) / P$ and the direction of RIS w.r.t. the ISAC BS with a relative strength of $\beta$. A larger trade-off factor $\beta < 1$ signifies a higher priority for the communication performance.

In Fig. 2(a) and Fig. 2(b), we compare the transmit beampattern and the worst-case target illumination power of our method (Proposed) with that of benchmark methods, namely, Unquantized radar [26] and Unquantized ISAC systems. We simulate Unquantized ISAC using the solution obtained by dropping the arc-sine constraint (5b). We wish to remark that the Unquantized radar [26] is designed to form peaks only towards the target directions and not towards the RIS. For low values of $\beta$, the worst-case target illumination power of the proposed method is comparable to that of Unquantized radar. As expected, more power is radiated towards the RIS for larger values of $\beta$ leading to smaller target illumination power. Furthermore, especially for moderate to large $\beta$, the beampatterns and the target illumination power of Proposed is comparable to that of Unquantized ISAC, demonstrating that the solution to the relaxed problem is close to that of the actual problem.

We present SEP of different methods in Fig. 2(c) and Fig. 2(d). MRT is the unquantized maximal ratio transmit precoder. $ZF$ is the zero forcing precoder and QMRT is the MRT with 1-bit quantization [3]. For benchmark schemes, RIS phase shifts are assumed to be of infinite precision (i.e., no quantization) and is selected to maximize the gain towards the user direction. Since the direct paths are blocked and the RIS as such cannot carry out any precoding due to its passive nature, serving multiple users at the same time leads to significantly high multi-user interference leading to high SEP. From Fig. 2(c), we observe that even for $K = 2$, an unquantized zero-forcing precoder with infinite precision RIS itself is not able to reliably serve all users. Hence, for the rest of the simulation, we assume that all users are served using TDM. The proposed method (RIST) with just 2 bits of RIS phase shift resolution is significantly better than that of QMRT since the impact of 1-bit DAC at the transmitter is alleviated by performing modulation using the RIS. With 4-bit resolution RIS, we perform significantly better than QMRT and close to RIST with continuous phase shifters in the considered setting.

From Fig. 2(d), we can observe that SEP of RIST decrease with an increase in $\beta$, which is expected since a larger $\beta$ radiates more power towards the RIS resulting in stronger modified channels $\alpha_n$ to the users. Even when $\beta = 0.1$ (i.e., less priority for communication), the proposed scheme with $b = 4$ offers an order of improvement in SEP when compared with QMRT, despite the latter using infinite precision RIS. Moreover, RIST with $b = 4$ already approaches the performance of RIST with $b = \infty$. Since the cost and complexity of RIS with $2 - 4$ bits of phase shift resolution is significantly less than that of using DACs with $2 - 4$ bits of resolution for each antenna at the ISAC BS, the proposed scheme is an attractive option for the next generation of wireless systems.

In this paper, we introduced a novel scheme where an RIS is introduced in an ISAC system with 1-bit DACs to mitigate the effects of coarse quantization and to enable coexistence of sensing and communication functionalities. Specifically, we designed the transmit precoders to obtain 1-bit radar waveforms that achieve certain desired communication functionalities. The RIS phase shifts are then designed to modulate the 1-bit radar waveform to send information to the users. The proposed scheme offers significantly better symbol error probabilities for users when compared with the state-of-the-art quantized MIMO systems while suffering from a moderate radar performance loss of about 1 to 2 dB compared to a MIMO radar system using infinite precision DACs.
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