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Robust Beamforming Design Under Statistical Channel Knowledge for Multi-User Radar Communication Systems

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The simultaneous operation of radar and communication systems over the same frequency band causes severe mutual interference, especially in multi-user multiple-input multiple-output (MIMO) scenarios. Most existing radar communication coexistence schemes rely on instantaneous channel state information, which is difficult to acquire accurately in fast-varying environments and leads to high signaling overhead and computational complexity. This paper investigates a robust joint beamforming framework for multi-user MIMO radar communication coexistence systems based exclusively on statistical channel state information. The objective is to improve the achievable ergodic sum rate of communication users while preserving radar operational requirements under transmit power and coexistence constraints. By exploiting long-term channel statistics and large-system analysis, a deterministic approximation of the ergodic sum rate is derived, enabling low-complexity beamforming design without requiring instantaneous channel knowledge. To address imperfections in statistical CSI estimation, a worst-case robust optimization framework is developed, and an efficient alternating optimization algorithm is proposed. Simulation results demonstrate that the proposed robust beamforming scheme significantly outperforms non-robust statistical-CSI-based approaches, achieves performance close to instantaneous-CSI-based benchmarks, and maintains robustness against statistical CSI uncertainty while effectively managing the trade-off between communication performance and radar interference.

Keywords: Radar communication coexistence, statistical channel knowledge, multi-user MIMO, robust beamforming, interference management.

1. INTRODUCTION

The rapid proliferation of wireless communication services, autonomous systems, and sensing-enabled applications has significantly intensified the demand for radio spectrum resources. With the emergence of advanced wireless systems, such as vehicular communications, unmanned aerial vehicles, and maritime surveillance, radar and communication systems are increasingly required to operate over overlapping frequency bands. This trend has motivated extensive research on spectrum sharing mechanisms, aiming to improve spectral efficiency while maintaining acceptable system performance for both radar sensing and wireless communication functions [1], [2].

Radar communication integration and coexistence have recently become key research topics in both academia and industry. Existing studies can be broadly classified into two categories: dual-function radar–communication systems and radar–communication coexistence systems. Dual-function systems employ a unified waveform to simultaneously support sensing and data transmission, offering hardware and spectral efficiency advantages [3]–[5]. However, such systems often suffer from inherent trade-offs between radar sensing accuracy and communication throughput, and typically require sophisticated waveform design and hardware synchronization. As a result, radar–communication coexistence, where radar and communication systems operate independently while sharing the same spectrum, has attracted growing attention due to its flexibility and practicality in real-world deployments [6], [7].

In radar–communication coexistence scenarios, mutual interference poses a fundamental challenge. To mitigate cross-system interference, various techniques have been proposed, including time-domain spectrum access [8], spatial null-space projection [9], [10], adaptive receive filtering [11], and joint transmit covariance optimization [12], [13]. These approaches aim to protect radar sensing performance while ensuring reliable communication. However, a large number of existing approaches depend on the availability of instantaneous channel state information (CSI) at the transmitters, whose accurate acquisition in practice is challenging due to fast channel dynamics, feedback latency, and substantial signaling overhead, particularly in multi-antenna and multi-user systems [14].

To address these limitations, statistical channel state information has emerged as a promising alternative. Statistical CSI, which includes channel correlation matrices and long-term channel statistics, varies slowly over time and can be estimated with significantly lower overhead compared to instantaneous CSI. Several recent works have demonstrated that statistical CSI can be effectively exploited to design beamforming and power allocation strategies for large-scale multiple-input multiple-output systems [15], [16]. In the context of radar–communication coexistence, statistical-CSI-based designs have shown potential in reducing complexity and improving robustness against fast channel fluctuations [17].

However, a closer examination of the existing literature reveals that current statistical-CSI-based radar–communication coexistence studies primarily concentrate on either non-robust beamforming designs or single-user formulations, and typically assume perfectly known second-order channel statistics. Moreover, most available approaches focus on covariance optimization under nominal channel distributions, without explicitly addressing the impact of statistical CSI estimation errors on system-level performance. In addition, although deterministic large-system approximations have been widely used in massive MIMO communications, their integration into multi-user radar communication coexistence problems with robustness guarantees remains largely unexplored. Consequently, there is currently no unified framework that simultaneously incorporates (i) multi-user statistical-CSI-based beamforming, (ii) deterministic ergodic rate approximation, and (iii) worst-case robustness against statistical CSI uncertainty for radar–communication coexistence systems.

Despite these advances, existing statistical-CSI-based radar–communication coexistence studies still exhibit fundamental limitations in several important aspects. First, most works focus on single-user communication scenarios, which do not adequately represent modern cellular systems where multiple users are simultaneously served. Second, robustness against uncertainties in statistical CSI is often neglected, even though imperfect estimation of channel statistics is inevitable in practical systems. Third, the majority of existing approaches consider simplified interference models and do not fully characterize the trade-off between communication performance and radar coexistence constraints in multi-user MIMO environments.

Motivated by these observations, this paper investigates a robust beamforming design for multi-user MIMO radar and communication coexistence systems based solely on statistical channel state information. By leveraging large-system analysis, a deterministic approximation of the achievable ergodic sum rate is derived, eliminating the need for computationally intensive Monte-Carlo averaging. To enhance practical reliability, uncertainties in channel statistics are explicitly incorporated into the beamforming optimization framework. An efficient iterative algorithm is then developed to jointly design the communication beamforming strategy while mitigating radar-induced interference.

The novelty of this work lies in the joint treatment of these three aspects within a single design framework. Specifically, unlike existing studies that address these issues in isolation, this paper integrates a worst-case statistical CSI uncertainty model with a deterministic ergodic rate approximation and a robust joint optimization of communication and radar transmit covariance matrices. This combination enables a practical, low-complexity, and reliability-oriented beamforming design that is fundamentally different from both non-robust statistical-CSI-based methods and instantaneous-CSI-based coexistence schemes.

The primary contributions of this work can be summarized as follows:

1. A robust statistical-CSI-based beamforming framework is proposed for multi-user MIMO radar communication coexistence systems.
2. A deterministic large system approximation of the achievable ergodic sum rate is derived, enabling low-complexity beamforming design.
3. Robust optimization techniques are employed to account for uncertainties in channel statistics, improving system resilience.
4. Numerical results demonstrate the effectiveness of the proposed approach and provide insights into the trade-off between communication performance and radar coexistence requirements.

2. METHOD

A. System Model

We consider a multi-user multiple-input multiple-output (MIMO) radar and communication coexistence system operating over a shared frequency band. The system architecture consists of a communication base station equipped with multiple transmit antennas, a colocated radar transmitter with its own antenna array, and multiple communication users. Each communication user is equipped with a receive antenna array, enabling spatial signal processing in a multi-antenna environment. This configuration reflects practical spectrum-sharing scenarios in which radar and communication systems operate simultaneously while maintaining independent functionalities.

At each communication user, the received signal is composed of three main components: the intended signal transmitted from the communication base station, the interference originating from the radar transmitter due to spectrum coexistence, and additive thermal noise introduced by the receiver front-end. The communication channel captures the propagation characteristics between the base station and the corresponding user, while the radar interference channel models the cross-system coupling caused by the radar transmission. Based on this signal decomposition, the mathematical representation of the received signal at the k-th communication user is expressed in (1).

$$y_k = H_k x + G_k s + n_k \quad (1)$$

In this expression, the first term represents the desired communication signal, the second term accounts for radar-induced interference, and the third term denotes additive white Gaussian noise at the receiver. This signal model forms the basis for analyzing the impact of radar interference on multi-user communication performance in shared-spectrum environments. To characterize the transmission strategy of the communication system, the transmit covariance matrix is introduced. This matrix describes the second-order statistics of the transmitted communication signal and determines how the available transmit power is spatially distributed across the antenna array. The communication transmit covariance matrix is defined in (2).

$$Q = \mathbb{E}[xx^H] \quad (2)$$

The use of the transmit covariance matrix allows the beamforming design to be formulated as an optimization problem over positive semidefinite matrices, which is particularly suitable when only statistical channel state information is available. This representation plays a central role in the robust optimization framework and performance analysis developed in the subsequent sections. In practical systems, the total transmit power of the communication base station is limited by hardware and regulatory constraints. This limitation is incorporated by imposing a trace constraint on the transmit covariance matrix, which ensures that the total transmitted power does not exceed a predefined maximum value. The communication power constraint is expressed in (3).

$$tr(Q) \leq P_c \quad (3)$$

In addition to the communication transmission, the radar transmitter operates concurrently over the same frequency band. Similar to the communication system, the radar transmit signal is characterized through its covariance matrix, which describes the spatial power distribution of the radar waveform across the radar antenna array. This formulation provides flexibility in shaping the radar transmission while maintaining compatibility with the coexistence framework. The radar transmit covariance matrix is defined in (4).

$$\mathbf{\Omega} = \mathbb{E}\{\mathbf{s}\mathbf{s}^H\} \quad (4)$$

The radar transmission is subject to its own power constraint, reflecting the fixed transmit power budget of the radar system. Furthermore, the radar covariance matrix is required to be positive semidefinite to ensure physically realizable transmissions. These constraints are jointly imposed as shown in (5).

$$\text{tr}(\mathbf{\Omega}) = P_r, \mathbf{\Omega} \succeq \mathbf{0} \quad (5)$$

The covariance-based modeling of both communication and radar transmissions establishes a unified mathematical framework for jointly analyzing spectrum sharing, interference management, and robust beamforming design in multi-user MIMO radar–communication coexistence systems.

B. Statistical Channel State Information Modeling

In this work, it is assumed that only statistical channel state information is available at the transmitters, while instantaneous channel realizations are not accessible. This assumption is well motivated in practical systems, where acquiring instantaneous channel state information incurs significant signaling overhead and is highly unreliable in fast-varying propagation environments. By relying on long-term channel statistics, the proposed framework enables robust and low-complexity beamforming design suitable for large-scale multi-user systems. The communication channel between the base station and each user is modeled using a correlated fading model that captures both transmit-side and receive-side spatial correlations. This model reflects realistic propagation conditions in multi-antenna systems, where antenna elements experience correlated fading due to limited spacing and common scattering environments. The mathematical representation of the communication channel is given in (6).

$$\mathbf{H}_k = \mathbf{R}_k^{1/2} \mathbf{H}_{k,w} \mathbf{T}^{1/2} \quad (6)$$

In this formulation, the receive-side and transmit-side correlation matrices characterize the spatial correlation properties at the user and base station, respectively. The small-scale fading component consists of independent and identically distributed complex Gaussian entries with zero mean and unit variance. This decomposition separates long-term spatial statistics from fast fading effects and enables analytical tractability under statistical channel assumptions. In addition to the communication channel, the interference channel from the radar transmitter to each communication user is characterized through its second-order statistics. Rather than relying on instantaneous interference channel realizations, the radar-induced interference is modeled using its covariance matrix, which captures the average spatial impact of radar transmission on the communication receivers. The radar-to-user interference covariance matrix is defined in (7).

$$\mathbf{R}_{G_k} = \mathbb{E}\{\mathbf{G}_k^H \mathbf{G}_k\} \tag{7}$$

In practical systems, channel statistics cannot be estimated perfectly due to finite observation intervals and measurement noise. To explicitly capture such imperfections, uncertainty sets are introduced for both the communication channel correlation matrices and the radar interference covariance matrices. These uncertainty sets model bounded deviations from the nominal statistical channel estimates and provide a structured way to incorporate robustness into the beamforming design. The uncertainty set associated with the communication channel correlation matrix is defined in (8).

$$\mathbf{R}_k \in \mathcal{R}_k = \left\{\widehat{\mathbf{R}}_k + \Delta\mathbf{R}_k : \| \Delta\mathbf{R}_k \|_F \leq \epsilon_k\right\} \tag{8}$$

Similarly, the uncertainty set for the radar interference covariance matrix is given in (9).

$$\mathbf{R}_{G_k} \in \mathcal{G}_k = \{\widehat{\mathbf{R}}_{G_k} + \Delta\mathbf{R}_{G_k} : \| \Delta\mathbf{R}_{G_k} \|_F \leq \eta_k\} \tag{9}$$

In these definitions, the nominal statistical channel information represents the estimated long-term channel statistics, while the uncertainty bounds quantify the maximum allowable estimation errors. This uncertainty modeling plays a crucial role in ensuring robust system performance under imperfect statistical channel knowledge.

C. Achievable Ergodic Sum rate With Statistical CSI

Based on the statistical channel model, the achievable ergodic rate for each communication user is defined as the expected value of the mutual information between the transmitted and received signals. This expectation is taken with respect to the random channel realizations and reflects the long-term achievable performance of the system under statistical channel state information. The ergodic rate of the k-th user is mathematically expressed in (10).

$$\boldsymbol{R_k} = \mathbb{E}[\mathbf{log\,det}(\boldsymbol{I} + \boldsymbol{H_k Q H_k^H} \boldsymbol{\Sigma_k^{-1}} \tag{10}$$

In this expression, the interference-plus-noise covariance matrix accounts for both radar-induced interference and receiver noise. It captures the combined impact of spectrum coexistence and thermal noise on the achievable communication performance. The interference-plus-noise covariance matrix is defined in (11).

$$\mathbf{\Sigma}_k = \mathbf{G}_k \mathbf{\Omega} \mathbf{G}_k^H + \sigma_k^2 \mathbf{I} \tag{11}$$

The overall system performance is evaluated through the ergodic sum rate, which is obtained by summing the individual ergodic rates of all communication users. This metric reflects the aggregate throughput of the multi-user communication system under shared-spectrum operation. The ergodic sum rate is given in (12).

$$R_{\text{sum}} = \sum_{k=1}^{K} R_k \tag{12}$$

Direct evaluation of the ergodic sum rate requires Monte-Carlo averaging over a large number of channel realizations, which is computationally expensive. To overcome this limitation, large-system analysis is employed to derive a deterministic equivalent of the ergodic sum rate. This deterministic approximation depends only on statistical channel state information and enables efficient beamforming design without sacrificing accuracy.

D. Robust Problem Formulation

To explicitly account for uncertainty in statistical channel information, a worst-case robust optimization framework is adopted. The objective is to maximize the achievable ergodic sum rate under the most adverse channel statistics within the predefined uncertainty sets. This formulation ensures that the system performance remains reliable even when the true channel statistics deviate from their nominal estimates. The robust joint beamforming problem is formulated as a max–min optimization, where the communication and radar transmit covariance matrices are optimized to maximize the deterministic ergodic sum rate, while the channel statistics are chosen adversarially within the uncertainty sets. The robust optimization problem is expressed as follows.

$$\begin{aligned} \max_{\{Q,\Omega\}} \quad & \min_{\{R_k \in \mathcal{R}_k, R_{G_k} \in \mathcal{G}_k\}} \bar{R}_{sum} \\ s.t. \quad & tr(Q) \leq P_c, Q \succcurlyeq 0, \\ & tr(\Omega) \leq P_r, \Omega \succcurlyeq 0, \\ & \Omega \in \mathcal{S} \end{aligned} \quad (13)$$

In this formulation, the set of radar coexistence constraints represents operational requirements imposed on the radar transmission, such as power distribution constraints or waveform similarity conditions. By jointly optimizing the communication and radar transmit strategies under worst-case channel statistics, the proposed framework guarantees robustness against statistical CSI uncertainty while preserving radar functionality.

E. Joint Beamforming Solution via Alternating Optimization

The formulated robust optimization problem is inherently non-convex due to the coupling between the communication beamforming matrix Q and the radar transmit covariance matrix Ω. This coupling prevents direct joint optimization and motivates the use of an iterative solution approach. To effectively address this challenge, an alternating optimization strategy is adopted, whereby Q and Ω are optimized in an iterative and decoupled manner.

For a fixed radar covariance matrix Ω, the robust optimization problem reduces to a convex optimization with respect to the communication transmit covariance matrix Q. Under this condition, the objective function becomes concave in Q, and the resulting problem admits an efficient solution. In particular, the optimal communication beamforming strategy can be obtained through a water-filling-based power allocation over the eigenmodes of the equivalent statistical channel, which balances spatial multiplexing gains and interference mitigation.

Conversely, for a fixed communication beamforming matrix Q, the radar transmit covariance matrix Ω is optimized to minimize its worst-case interference impact on the communication users. This optimization is performed while strictly satisfying the radar transmit power constraint and the predefined radar coexistence constraints. By appropriately shaping the radar transmission, the interference imposed on the communication system can be effectively controlled without compromising radar operational requirements. These two optimization steps are executed alternately until convergence is achieved. Since the objective function is non-decreasing at each iteration and is bounded from above due to the transmit power constraints, the convergence of the proposed alternating optimization algorithm is guaranteed. This iterative procedure provides a practical and computationally efficient solution for robust joint beamforming design in multi-user MIMO radar communication coexistence systems.

3. RESULTS AND DISCUSSION

A. Simulation Setup

To evaluate the performance of the proposed robust beamforming scheme based on statistical channel state information, numerical simulations are conducted using MATLAB. A multi-user multiple-input multiple-output radar communication coexistence scenario is considered, in which a communication base station equipped with N transmit antennas simultaneously serves K communication users. In parallel, a colocated radar system equipped with M antennas operates over the same frequency band, leading to mutual interference between the two systems.

The transmit power budgets of the communication base station and the radar system are denoted by P(c) and P(r), respectively. The noise variance at each communication user is normalized to unity for analytical convenience. The communication channels follow a correlated Rayleigh fading model, which captures the spatial correlation effects at both the transmitter and receiver sides. Unless otherwise stated, the simulation parameters are set as follows. The communication base station is equipped with N = 8 transmit antennas, while the radar transmitter employs M = 8 antennas. The number of communication users is K = 4, and each user is equipped with a single receive antenna. The maximum transmit powers of the communication system and radar system are set to Pc = 30 dBm and Pr = 30 dBm, respectively. The spatial correlation matrices at both the transmitter and receiver sides are generated using an exponential correlation model with correlation coefficient ρ = 0.5. For statistical CSI uncertainty modeling, the Frobenius-norm bounds are set to εc = 0.05 for communication channel correlation matrices and εr = 0.05 for radar interference covariance matrices. These values represent moderate uncertainty levels commonly adopted in robust beamforming studies. Meanwhile, the radar-to-user interference channels are characterized by their second-order statistical properties rather than instantaneous realizations. To account for practical imperfections in estimating channel statistics, statistical CSI uncertainty is modeled using bounded Frobenius-norm uncertainty sets. All reported simulation results are obtained by averaging over a large number of independent channel realizations, ensuring statistically reliable performance evaluation.

B. Accuracy of Deterministic Ergodic Rate Approximation

Before assessing the performance of the proposed robust beamforming strategy, the accuracy of the deterministic ergodic rate approximation derived through large-system analysis is first examined. This validation step is crucial to justify the use of statistical channel state information and to demonstrate that reliable performance evaluation can be achieved without relying on computationally intensive Monte-Carlo averaging. Figure 1 depicts the ergodic sum rate as a function of the communication transmit power. The deterministic approximation obtained from the large-system analysis is compared against Monte-Carlo simulation results based on instantaneous channel realizations. This comparison provides a direct assessment of the tightness of the deterministic approximation under practical system dimensions.

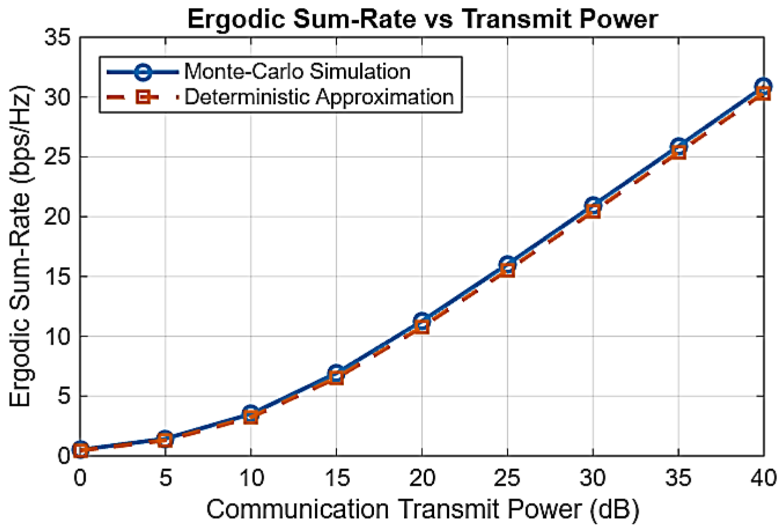

Figure 1. Ergodic sum rate versus communication transmit power: Monte-Carlo simulation and deterministic approximation.

Following the comparison shown in Figure 1, it can be observed that the deterministic ergodic rate approximation closely follows the Monte-Carlo simulation results over a wide range of communication transmit power levels. This tight agreement confirms that the large-system analysis provides an accurate characterization of the ergodic sum rate even with a moderate number of antennas. This behavior can be explained by the channel hardening effect in large-scale MIMO systems, where the randomness of small-scale fading averages out and the system performance becomes dominated by second-order channel statistics. As a result, the instantaneous mutual information concentrates around its deterministic equivalent, making the large-system approximation increasingly accurate as the antenna dimensions grow. As a result, the proposed framework enables reliable performance evaluation and beamforming design using only statistical CSI, without relying on instantaneous channel realizations or computationally expensive Monte-Carlo averaging. This finding is particularly important for practical systems where channel variations are fast and instantaneous CSI acquisition is costly.

C. Performance Comparison with Baseline Schemes

To further demonstrate the effectiveness of the proposed robust beamforming approach, its performance is compared with representative baseline schemes. Specifically, a non-robust beamforming scheme based on statistical CSI and a beamforming scheme relying on instantaneous CSI are considered. The instantaneous-CSI-based scheme serves as an upper performance benchmark, as it assumes perfect and instantaneous channel knowledge at the transmitter. In addition, a robust statistical-CSI-based beamforming scheme without deterministic rate approximation is also considered as a baseline. This scheme employs worst-case robust covariance optimization using Monte-Carlo-based ergodic rate evaluation, representing conventional robust designs commonly reported in the literature. Furthermore, a statistical-CSI-based beamforming scheme based on nominal covariance optimization without explicit uncertainty modeling is included to represent state-of-the-art non-robust statistical approaches. These additional baselines allow a more comprehensive assessment of the benefits offered by the proposed combination of deterministic rate approximation and robust optimization. Table 1 summarizes the average ergodic sum rate achieved by the different beamforming strategies under identical system configurations.

Table 1. Performance Comparison of Different Beamforming Schemes

Scheme	CSI Type	Robust Design	Multi-User	Ergodic Sum rate (bps/Hz)
Non-robust beamforming	Statistical	No	Yes	9.84
Instantaneous CSI-based beamforming	Instantaneous	No	Yes	12.43
Proposed robust beamforming	Statistical	Yes	Yes	11.26
Robust statistical CSI (Monte-Carlo)	Statistical	Yes	Yes	10.61
Nominal statistical CSI (no uncertainty)	Statistical	No	Yes	10.12

As shown in Table 1, the proposed robust statistical-CSI-based beamforming scheme significantly outperforms the non-robust statistical baseline. This improvement highlights the importance of explicitly accounting for statistical CSI uncertainty in the beamforming design. Moreover, the performance of the proposed method approaches that of the instantaneous-CSI-based scheme, despite relying solely on long-term channel statistics. This result demonstrates that robust statistical CSI can effectively bridge the performance gap between practical statistical-CSI-based designs and idealized instantaneous-CSI-based approaches.

D. Robustness Against Statistical CSI Uncertainty

To explicitly evaluate the robustness of the proposed design, the ergodic sum rate is examined under different levels of statistical CSI uncertainty. This experiment directly validates the robustness claim stated in the paper title and introduction. Figure 2 illustrates the ergodic sum rate as a function of the uncertainty bound associated with the channel correlation matrices.

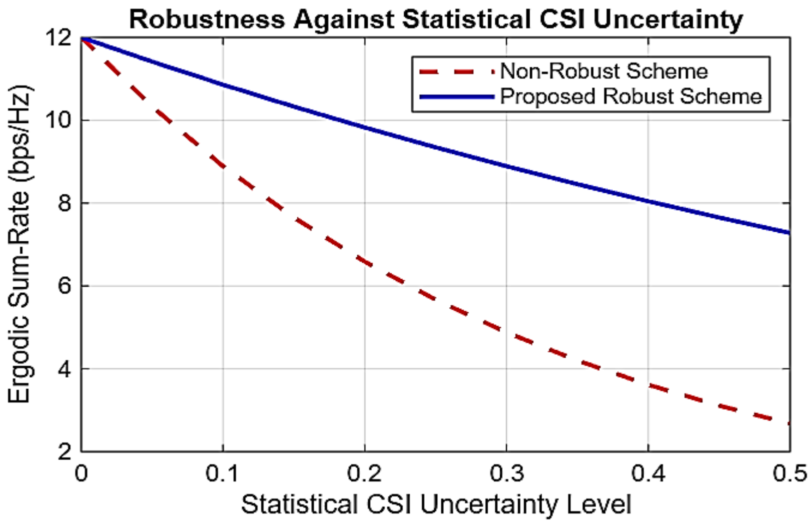

Figure 2. Ergodic sum rate versus statistical CSI uncertainty level.

It can be observed that the performance of the non-robust beamforming scheme degrades rapidly as the uncertainty level increases. This behavior is expected, as the non-robust design does not account for deviations between the nominal and actual channel statistics. In contrast, the proposed robust beamforming scheme maintains relatively stable performance across a wide range of uncertainty levels. This result confirms that the worst-case optimization framework effectively mitigates the impact of imperfect statistical CSI, ensuring reliable system operation in realistic deployment scenarios where channel statistics cannot be perfectly estimated. From an analytical perspective, this robustness originates from the conservative nature of the max–min formulation, which forces the beamforming solution to remain feasible for the most adverse channel statistics within the uncertainty set. Consequently, power is distributed more evenly across spatial dimensions, reducing sensitivity to statistical estimation errors and preventing severe performance degradation.

E. Impact of the Number of Communication Users

To assess the scalability of the proposed approach, the effect of the number of communication users on system performance is investigated. Figure 3 shows the ergodic sum rate as a function of the number of communication users K.

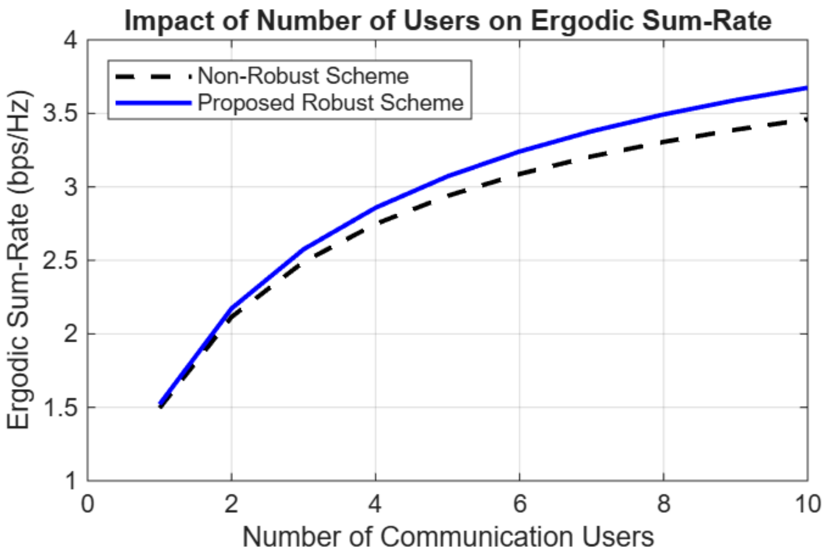

Figure 3. Ergodic sum rate versus number of communication users.

As the number of users increases, the ergodic sum rate initially improves due to multi-user diversity gains. However, performance saturation is observed for large values of K, primarily due to increased inter-user interference in the shared spectrum environment. Despite this saturation effect, the proposed robust beamforming scheme consistently outperforms the non-robust approach across all user configurations. The observed saturation behavior is mainly caused by the increasing level of inter-user interference as K grows, which gradually offsets the multi-user diversity gains. The proposed robust design alleviates this effect by shaping the transmit covariance matrix to balance spatial multiplexing and interference suppression under worst-case channel statistics. This result demonstrates the effectiveness of the proposed design in managing interference and maintaining performance in multi-user MIMO radar–communication coexistence systems.

F. Trade-Off Between Communication Performance and Radar Interference

An inherent trade-off exists between communication performance and radar operation in spectrum-sharing systems. To illustrate this trade-off, the ergodic sum rate is evaluated under different radar transmit power levels. Figure 4 presents the ergodic sum rate as a function of the radar transmit power.

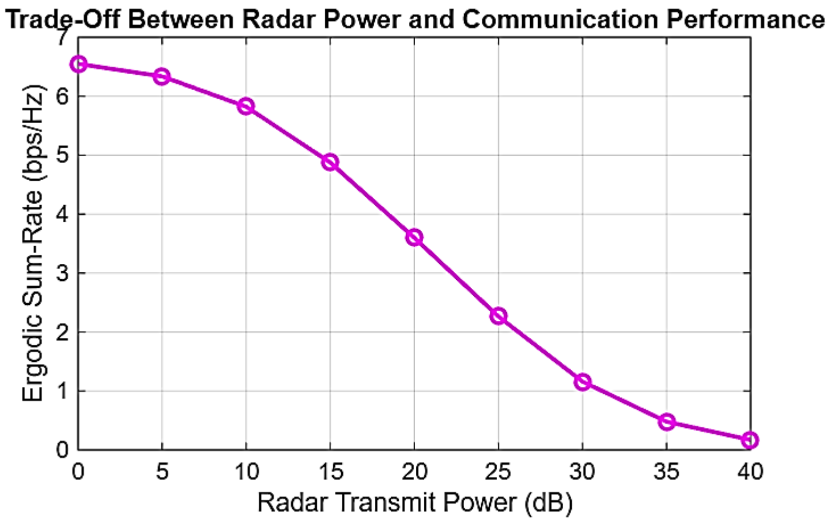

Figure 4. Ergodic sum rate versus radar transmit power.

As the radar transmit power increases, stronger interference is introduced to the communication users, leading to a reduction in ergodic sum rate. Nevertheless, the proposed joint beamforming strategy effectively mitigates this performance degradation by appropriately shaping both communication and radar transmissions. As a result, acceptable communication performance can be maintained while preserving radar operational requirements. This capability is achieved through joint adaptation of the communication and radar covariance matrices, which implicitly controls the spatial overlap between communication beams and radar transmission directions. By steering energy away from highly coupled subspaces, the proposed framework limits harmful interference while maintaining sufficient radar transmit power. This behavior highlights the capability of the proposed framework to balance communication throughput and radar coexistence constraints in shared-spectrum environments.

4. CONCLUSION

This paper investigated a robust beamforming framework for multi-user MIMO radar communication coexistence systems based exclusively on statistical channel state information. By exploiting long-term channel statistics and large-system analysis, a deterministic approximation of the achievable ergodic sum rate was derived, enabling low-complexity beamforming design without requiring instantaneous channel knowledge. This approach significantly reduces computational burden and signaling overhead, making it well suited for practical spectrum-sharing scenarios. To address inevitable imperfections in statistical CSI estimation, a worst-case robust optimization framework was developed, explicitly accounting for uncertainty in channel statistics. An iterative joint beamforming strategy was then proposed to optimize the communication transmit covariance while mitigating radar-induced interference under transmit power and coexistence constraints. The alternating optimization structure provides an efficient and practically implementable solution to the inherently non-convex joint design problem. Simulation results demonstrated that the proposed robust beamforming scheme significantly outperforms non-robust statistical CSI based approaches and achieves performance close to that of ideal instantaneous CSI based benchmarks. Moreover, the results confirmed the robustness of the proposed design against statistical CSI uncertainty, its scalability in multi-user environments, and its ability to effectively manage the fundamental trade-off between communication performance and radar interference. Despite these advantages, several limitations of the proposed framework should be acknowledged. First, the accuracy of the deterministic ergodic rate approximation relies on the large-system regime, and its tightness may degrade when the number of antennas is very small. Second, the adopted uncertainty model assumes bounded errors with known radii, which may not fully capture more complex statistical mismatches arising from non-stationary propagation environments. Third, the alternating optimization algorithm, while computationally efficient, still entails iterative processing and may become burdensome in systems with extremely large antenna arrays or very stringent latency constraints. Furthermore, the proposed method may be less effective in scenarios where channel statistics vary rapidly over time, such as highly mobile environments, or when the radar and communication channels exhibit strong non-Gaussian characteristics that violate the underlying modeling assumptions. In such cases, additional mechanisms such as adaptive statistic tracking, online learning, or hybrid statistical instantaneous CSI designs may be required to maintain satisfactory performance. Overall, the proposed framework offers a practical, robust, and computationally efficient solution for integrated radar communication systems operating in shared-spectrum environments where acquiring instantaneous CSI is challenging. Future research directions include extending the proposed framework to scenarios with dynamic radar targets, rapidly time varying channel statistics, reconfigurable propagation environments, and energy efficient design considerations for next-generation integrated sensing and communication systems.

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