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Robust design for IRS-assisted multiuser systems under practical imperfections: a rate-splitting approach

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Key words: Intelligent reflecting surface; Rate-splitting multiple access; Discrete phase shifts; Hardware impairments; Imperfect channel state information; Robust beamforming

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Background

1. The next-generation wireless communication systems aim to enhance existing 5G technologies while exploring novel solutions to support ultra-high data rates and massive connectivity.
2. Intelligent reflecting surface (IRS) has emerged as a key technology for next-generation systems due to its low cost, wide coverage, and ability to adaptively control wireless propagation environments

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Motivation

1. The performance of IRS-assisted systems suffers significant degradation due to inevitable imperfections.
   - Hardware impairments (transceiver distortion)
   - Imperfect channel state information (CSI)
   - Discrete phase shifts (DPS) at IRS

2. Rate-splitting multiple access (RSMA) technology demonstrates strong robustness against inevitable imperfections. However the recent studies typically address only pairwise combinations of these three inevitable imperfections. Reasonably, the algorithm must simultaneously address both DPS and hardware imperfection.

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Main idea

1. We provide an IRS-aided multiuser RSMA framework under practical imperfections, including transceiver hardware impairment, DPSs, and imperfect CSI. Through leveraging the relationship between ergodic and average rates for both common and private streams, a stochastic optimization problem is formulated to enhance system performance.
2. To solve the challenging stochastic problem, we develop a sample average approximation (SAA)-based robust algorithm by exploiting the relationship between the weighted sum rate and weighted minimum mean square error (WMMSE).
3. Simulation results demonstrate that the proposed algorithm outperforms benchmark algorithms and provides practical insights for implementing IRS-assisted multiuser RSMA systems.

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System model

1. The received signal at the k^{th} user can be expressed as

$$y_k = \left(\boldsymbol{h}_{\mathrm{BU},k}^{\mathrm{H}} + \boldsymbol{\xi}^{\mathrm{T}} \boldsymbol{H}_{\mathrm{eff},k}^{\mathrm{H}}\right) \boldsymbol{x} + n_k + \kappa_{\mathrm{R},k}$$

where $\boldsymbol{H}_{\mathrm{eff},k} = \tilde{\boldsymbol{H}}_{\mathrm{eff},k} + \Delta \boldsymbol{H}_{\mathrm{eff},k}, \boldsymbol{h}_{\mathrm{BU},k} = \tilde{\boldsymbol{h}}_{\mathrm{BU},k} + \Delta \boldsymbol{h}_{\mathrm{BU},k}$ enotes the direct and the cascaded link CSI with errors, and $\kappa_{\mathrm{R},k} \sim \mathcal{CN}\left(\mathbf{0}, \beta_{\mathrm{R},k}^2 \mathbb{E}\left\{\tilde{y}_k \tilde{y}_k^{\mathrm{H}}\right\}\right)$ is the receiver distortion noise.

2. $\boldsymbol{x} = \boldsymbol{w}_{\mathrm{c}} s_{\mathrm{c}} + \sum_{k=1}^{K} \boldsymbol{w}_{\mathrm{p},k} s_{\mathrm{p},k} + \boldsymbol{\kappa}_{\mathrm{T}}$ is the transmit RSMA signal.

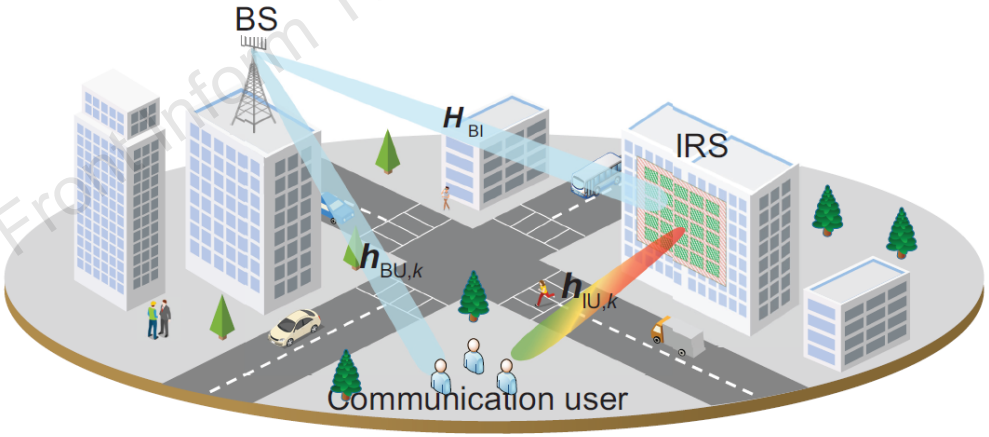


Fig. 1 An IRS-aided multiuser RSMA communication system. BS: base station; IRS: intelligent reflecting surface; RSMA: rate-splitting multiple access

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Problem formulation

1. The sum rate maximization problem with imperfect CSI can be formulated by

$$\begin{aligned}
\max_{\boldsymbol{W},\boldsymbol{\xi},\bar{r}_{\mathrm{c},k}} \quad & \sum_{k=1}^{K} \eta_k \left(\bar{r}_{\mathrm{c},k} + \bar{R}_{\mathrm{p},k}\right) \\
\text{s.t.} \quad & \left(1+\beta_{\mathrm{T}}^2\right) \mathrm{tr}\left(\boldsymbol{W}\boldsymbol{W}^{\mathrm{H}}\right) \le P, \\
& \sum_{k=1}^{K} \bar{r}_{\mathrm{c},k} \le \bar{R}_{\mathrm{c},k}, \ \forall k \in [1,K], \\
& \bar{r}_{\mathrm{c},k} + \bar{R}_{\mathrm{p},k} \ge R_k^{\mathrm{th}}, \ \forall k \in [1,K] \\
& \theta_m \in \mathbb{T}, \ \forall m \in [1,N_{\mathrm{I}}],
\end{aligned}$$

2. Based on the SAA and WWMSE methods, the problem can be transformed into a deterministic problem:

$$\begin{aligned}
\max_{\boldsymbol{W},\boldsymbol{\xi},\bar{r}_{\mathrm{c},k}} \quad & \sum_{k=1}^{K} \eta_k \left(\bar{r}_{\mathrm{c},k} + \frac{1}{A}\sum_{a=1}^{A} \hat{R}_{\mathrm{p},k}^{a}\right) \\
\text{s.t.} \quad & \left(1+\beta_{\mathrm{T}}^2\right) \mathrm{tr}\left(\boldsymbol{W}\boldsymbol{W}^{\mathrm{H}}\right) \le P, \ \theta_m \in \mathbb{T}, \ \forall m \in [1,N_{\mathrm{I}}], \\
& \sum_{k=1}^{K} \bar{r}_{\mathrm{c},k} \le \frac{1}{A}\sum_{a=1}^{A} \hat{R}_{\mathrm{c},k}^{a}, \ \forall k \in [1,K], \\
& \bar{r}_{\mathrm{c},k} + \frac{1}{A}\sum_{a=1}^{A} \hat{R}_{\mathrm{p},k}^{a} \ge R_k^{\mathrm{th}}, \ \forall k \in [1,K].
\end{aligned}$$

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Method

We divide the optimization variables into two sub-problems, corresponding to one block, while fixing the others.

1. With a fixed IRS phase shift matrix, the sub-problem for optimizing the block can be rewritten into

$$\max_{\boldsymbol{W},\bar{r}_{\mathrm{c},k}} \sum_{k=1}^{K} \eta_k \bar{r}_{\mathrm{c},k} - \sum_{k=1}^{K} \eta_k \boldsymbol{w}_{\mathrm{c}}^{\mathrm{H}} \boldsymbol{\Lambda}_{\mathrm{p},k}^{\mathrm{w}} \boldsymbol{w}_{\mathrm{c}} - \sum_{k=1}^{K} \eta_k \left(\sum_{j=1}^{K} \boldsymbol{w}_{\mathrm{p},j}^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{p},k}^{\mathrm{w}} \boldsymbol{w}_{\mathrm{p},j} \right) + 2 \sum_{k=1}^{K} \eta_k \mathrm{Re} \left\{ \left(\boldsymbol{\psi}_{\mathrm{p},k}^{\mathrm{w}} \right)^{\mathrm{H}} \boldsymbol{w}_{p.k} \right\}$$

$$\text{s.t.} \quad \boldsymbol{w}_{\mathrm{c}}^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{c},k}^{w} \boldsymbol{w}_{\mathrm{c}} + \sum_{j=1}^{K} \boldsymbol{w}_{\mathrm{p},j}^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{c},k}^{w} \boldsymbol{w}_{\mathrm{p},j} - 2\mathrm{Re} \left\{ \left(\boldsymbol{\psi}_{\mathrm{c},k}^{\mathrm{w}} \right)^{\mathrm{H}} \boldsymbol{w}_{\mathrm{p},k} \right\} \leq \beta_{\mathrm{c},k}^{\mathrm{w}} - \sum_{k=1}^{K} \bar{r}_{\mathrm{c},k}, \forall k \in [1, K],$$

$$\sum_{j=1}^{K} \boldsymbol{w}_{\mathrm{p},j}^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{p},k}^{\mathrm{w}} \boldsymbol{w}_{\mathrm{p},j} + \boldsymbol{w}_{\mathrm{c}}^{\mathrm{H}} \boldsymbol{\Lambda}_{\mathrm{p},k}^{\mathrm{w}} \boldsymbol{w}_{\mathrm{c}} - 2\mathrm{Re} \left\{ \left(\boldsymbol{\psi}_{\mathrm{p},k}^{\mathrm{w}} \right)^{\mathrm{H}} \boldsymbol{w}_{\mathrm{c}} \right\} - \bar{r}_{\mathrm{c}} \leq \beta_{\mathrm{p},k}^{\mathrm{w}} - R_k^{\mathrm{th}}, \forall k \in [1, K].$$

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This problem is convex and can be efficiently solved using standard interior-point methods.

Method

2. With a fixed beamforming at the BS, the sub-problem for optimizing the IRS phase shifts can be formulated as

$$\min_{\boldsymbol{\xi},\{\boldsymbol{z}_i\}_{i=1}^{2K+1}} \sum_{k=1}^{K} \eta_k \boldsymbol{\xi}^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{p},k}^{\xi} \boldsymbol{\xi} - 2\sum_{k=1}^{K} \eta_k \mathrm{Re}\left\{\boldsymbol{\xi}^{\mathrm{H}} \boldsymbol{\psi}_{\mathrm{p},k}^{\xi}\right\} + \rho \sum_{i-1}^{2K+1} \left\|\boldsymbol{z}_i - \boldsymbol{\xi} + \boldsymbol{\mu}_i\right\|^2$$

$$\begin{aligned}
\text{s.t.} \quad & \angle[\boldsymbol{z}_{2K+1}]_m \in \mathbb{T}, \forall m \in [1, N_{\mathrm{I}}], \\
& \boldsymbol{z}_k^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{c},k}^{\xi} \boldsymbol{z}_k - 2\mathrm{Re}\left\{\boldsymbol{z}_k^{\mathrm{H}} \boldsymbol{\psi}_{\mathrm{c},k}^{\xi}\right\} \leq \beta_{\mathrm{c},k}^{\xi} - \sum_{k=1}^{K} \bar{r}_{\mathrm{c},k}, \forall k \in [1, K], \\
& \boldsymbol{z}_{K+k}^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{p},k}^{\xi} \boldsymbol{z}_{K+k} - 2\mathrm{Re}\left\{\boldsymbol{z}_{K+k}^{\mathrm{H}} \boldsymbol{\psi}_{\mathrm{p},k}^{\xi}\right\} \leq \beta_{\mathrm{p},k}^{\xi} - R_k^{\mathrm{th}} + \bar{r}_{\mathrm{c},k}, \forall k \in [1, K]
\end{aligned}$$

By using the ADMM method, the above can be solved efficiently:

$$\boldsymbol{\xi} = \left(\sum_{k=1}^{K} \eta_k \boldsymbol{\Omega}_{\mathrm{p},k}^{\xi} + (2K+1)\rho \boldsymbol{I}_{N_I}\right)^{-1} \left[\sum_{k=1}^{K} \eta_k \boldsymbol{\psi}_{\mathrm{p},k}^{\xi} + \rho \sum_{i=1}^{2K+1} (\boldsymbol{z}_i + \boldsymbol{\mu}_i)\right]$$

$$\boldsymbol{z}_k = \left(\eta_{1,k} \boldsymbol{\Omega}_{\mathrm{c},k}^{\xi} + \boldsymbol{I}\right)^{-1} \left(\eta_{1,k} \boldsymbol{\psi}_{\mathrm{c},k}^{\xi} - \boldsymbol{\mu}_k + \boldsymbol{\xi}\right), \quad \forall k \in [1, K],$$

$$\boldsymbol{z}_{K+k} = \left(\eta_{2,k} \boldsymbol{\Omega}_{\mathrm{p},k}^{\xi} + \boldsymbol{I}\right)^{-1} \left(\eta_{2,k} \boldsymbol{\psi}_{\mathrm{p},k}^{\xi} - \boldsymbol{\mu}_{K+k} + \boldsymbol{\xi}\right),$$

$$\boldsymbol{z}_{2K+1} = \mathrm{e}^{\mathrm{j}(\arg\min_{\boldsymbol{\vartheta} \in \mathrm{T}} \{\mathrm{mod}\ (|\boldsymbol{\vartheta} - \angle \boldsymbol{\varsigma}|, 2\pi) - \pi\})}.$$

$$\eta_{2,k} = \min\left\{\eta_{2,k} \geq 0 : \boldsymbol{z}_{K+k}^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{p},k}^{\xi} \boldsymbol{z}_{K+k} - 2\mathrm{Re}\left\{\boldsymbol{z}_{K+k}^{\mathrm{H}} \boldsymbol{\psi}_{\mathrm{p},k}^{\xi}\right\} \leq \beta_{\mathrm{p},k} - R_k^{\mathrm{th}} + \bar{r}_{\mathrm{c},k}^{\xi}\right\}.$$

$$\eta_{1,k} = \min\left\{\eta_{1,k} \geq 0 : \boldsymbol{z}_k^{\mathrm{H}} \boldsymbol{\Omega}_{\mathrm{c},k}^{\xi} \boldsymbol{z}_k - 2\mathrm{Re}\left\{\boldsymbol{z}_k^{\mathrm{H}} \boldsymbol{\psi}_{\mathrm{c},k}^{\xi}\right\} \leq \beta_{\mathrm{c},k}^{\xi} - \sum_{k=1}^{K} \bar{r}_{\mathrm{c},k}\right\}.$$

$$\boldsymbol{\mu}_i \leftarrow \boldsymbol{z}_i - \boldsymbol{\xi} + \boldsymbol{\mu}_i, \forall i \in [1, 2K+1].$$

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Major results

1. The IRS-assisted RSMA system consistently outperforms its SDMA counterpart across all scenarios, including variations in DPSs (Fig. 3), hardware distortion levels, and CSI errors (Fig. 4). These results highlight the robustness of IRS-assisted RSMA, demonstrating its superior capability to mitigate practical limitations.

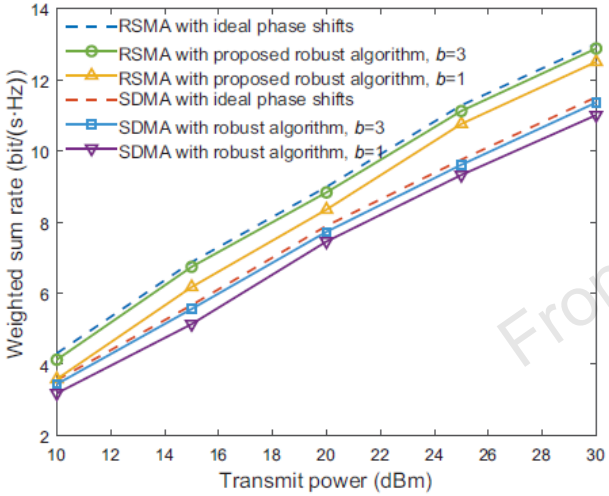


Fig. 3 Performance comparison between RSMA and SDMA under different quantization numbers. RSMA: rate-splitting multiple access; SDMA: space division multiple access

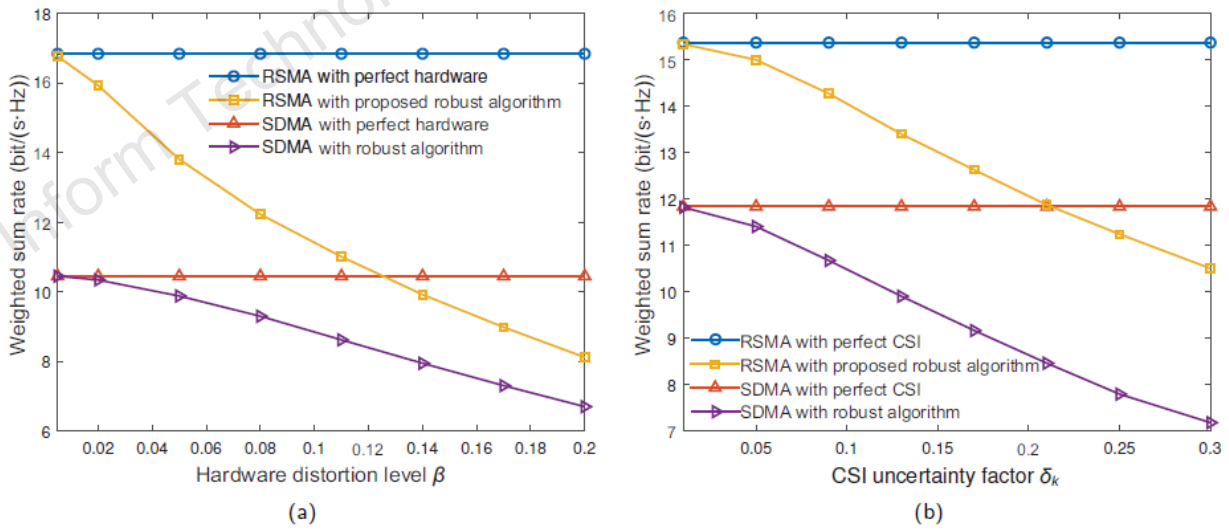


Fig. 4 Impacts of hardware distortion level (a) and CSI estimation errors (b). CSI: channel state information; RSMA: rate-splitting multiple access; SDMA: space division multiple access

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Major results

2. The impact of the number of IRS elements on system performance is analyzed. As shown in Fig. 5, increasing the number of IRS elements significantly enhances system performance. Additionally, the proposed RSMA-based algorithm outperforms the SDMA-based benchmark scheme, highlighting the superior robustness of RSMA under practical imperfections.

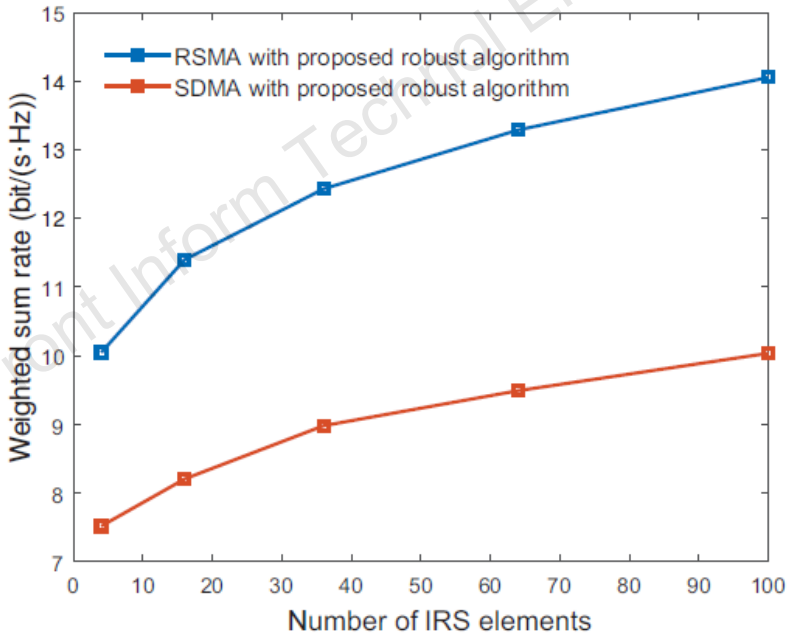


Fig. 5 Impact of the number of IRS elements on system performance. IRS: intelligent reflecting surface; RSMA: rate-splitting multiple access; SDMA: space division multiple access

Major results

Fig. 6 illustrates the impact of hardware distortions on system performance. The proposed robust algorithm consistently outperforms the benchmark algorithms, demonstrating its superior capability to mitigate hardware impairments and improve the overall system performance.

Fig. 7 illustrates the impact of CSI estimation errors on system performance. By increasing the hardware impairment level, a clear performance floor is observed in Fig. 7 due to the presence of imperfections. This underscores the importance of developing robust algorithms that jointly account for CSI errors and hardware distortions to improve system performance.

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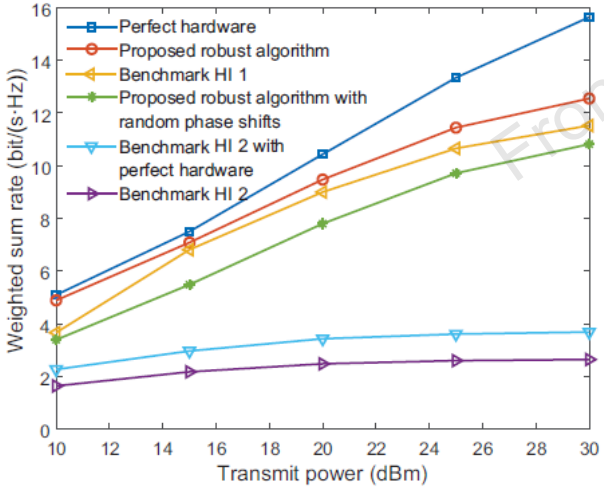


Fig. 6 Performance comparison of different beamforming design algorithms under hardware distortions

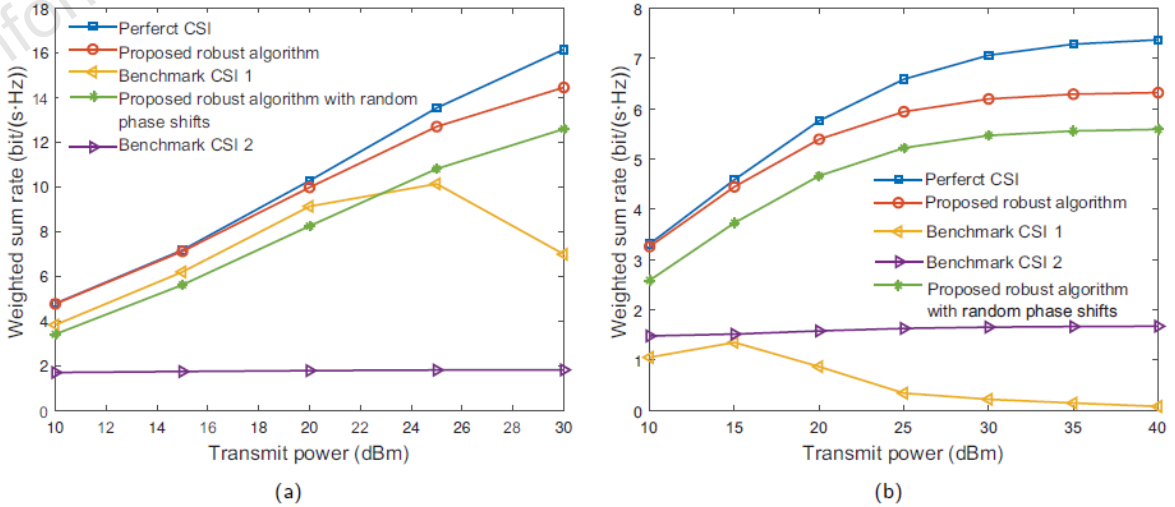


Fig. 7 Performance comparison of different beamforming design algorithms under imperfect CSI with $\beta_{\mathrm{T}} = \beta_{\mathrm{R}} = \beta = 0.08$ (a) and with $\beta_{\mathrm{T}} = \beta_{\mathrm{R}} = \beta = 0.3$ (b). CSI: channel state information

Conclusions

1. Unified framework for IRS-RSMA under hardware impairments, imperfect CSI, and DPS.

2. Novel SAA-based robust algorithm with closed-form updates and ADMM-based DPS optimization.

3. Key findings:

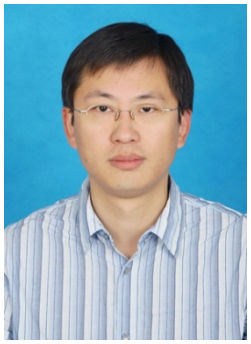
- RSMA provides stronger robustness than SDMA in imperfect environments.
- Proposed algorithm outperforms existing benchmarks in all tested scenarios.
- Efficient DPS design (3-bit) suffices for robust performance.

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