Efficacy of Multiuser Massive MISO Wireless Energy Transfer under IQ Imbalance and Channel Estimation Errors over Rician Fading

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Introduction and Background

Wireless power transfer from RF source to energy harvesting (EH) IoT [1]:

- Massive antenna array source: long range wireless power transfer (WPT)
- Accurate CSI is required at RF source for realizing full array gains
- Low cost hardware for economically viable ubiquitous deployment of IoT
- Low quality RF components are prone to hardware imperfections [2]
- Significant EH performance degradation due to underlying in-phase and quadrature-phase imbalance (IQI) and its impact on CE errors [3]

State of the art:

- IQI generates a virtual image [4] of RX at the multiantenna TX
- IQI estimation and compensation for MISO information transfer (IT) [5]
- Degradation in DL IT performance due to joint IQI and CE errors [3]
- Impact of CE errors on WPT from massive antenna TX with no IQI [6]

Motivation:

- Investigating the impact of IQI on efficacy of MU massive MISO WPT
- Rician fading model for incorporating strong LoS component in WPT
- More robust Least Squares (LS) based CE for TX precoder design

Key Contribution

- Obtain Rician channel estimate in MU massive MISO WPT under IQI
- Quantifying the degradation in optimized sum harvested power among EH users due to the joint IQI and CE (for LS and LMMSE) errors

System Description

- WPT from N antenna RF source $\mathcal{S}$ to the M single antenna EH users $\boldsymbol{\mathcal{U}}$
- Flat quasi-static Rician block fading with coherence interval of τ samples
- $\mathcal{S}$–to–$\mathcal{U}_i$ channel: $\mathbf{h}_i = \sqrt{\frac{\beta_i K_i}{K_i+1}}\mathbf{h}_{d_i} + \sqrt{\frac{\beta_i}{K_i+1}}\mathbf{h}_{s_i}, \quad \forall\, i = 1, 2, \ldots, M$
- With channel reciprocity, DL CE using UL pilot transmission from users
- Baseband TX IQI in pilot matrix $\mathbf{S}_{\mathrm{p}}$ during UL transmission from $\boldsymbol{\mathcal{U}}$ [2]

$$\mathbf{S}_{\mathrm{pTI}} = \mathbf{T}_{\mathcal{U}1}\,\mathbf{S}_{\mathrm{p}} + \mathbf{T}_{\mathcal{U}2}\,\mathbf{S}_{\mathrm{p}}^{*}. \tag{1}$$

with diagonal matrices $[\mathbf{T}_{\mathcal{U}1}]_i \triangleq \frac{1+g_{\mathrm{T}_{\mathcal{U}i}} \mathrm{e}^{j\phi_{\mathrm{T}_{\mathcal{U}i}}}}{2}$ and $[\mathbf{T}_{\mathcal{U}2}]_i \triangleq \frac{1-g_{\mathrm{T}_{\mathcal{U}i}} \mathrm{e}^{j\phi_{\mathrm{T}_{\mathcal{U}i}}}}{2}$, where $g_{\mathrm{T}_{\mathcal{U}i}}$ and $\phi_{\mathrm{T}_{\mathcal{U}i}}$ respectively denote the TX amplitude and phase mismatch

- Baseband RX IQI in received signal $\mathbf{Y}$ at $\mathcal{S}$ from $\boldsymbol{\mathcal{U}}$ during CE phase [2]

$$\mathbf{Y}_{\mathrm{RI}} = \mathbf{R}_{\mathcal{S}1}\,\mathbf{Y} + \mathbf{R}_{\mathcal{S}2}\,\mathbf{Y}^{*}, \tag{2}$$

with diagonal matrices $[\mathbf{R}_{\mathcal{S}1}]_i \triangleq \frac{1+g_{\mathrm{R}_{\mathcal{S}i}} \mathrm{e}^{-j\phi_{\mathrm{R}_{\mathcal{S}i}}}}{2}$ and $[\mathbf{R}_{\mathcal{S}2}]_i \triangleq \frac{1-g_{\mathrm{R}_{\mathcal{S}i}} \mathrm{e}^{j\phi_{\mathrm{R}_{\mathcal{S}i}}}}{2}$, where $g_{\mathrm{R}_{\mathcal{S}i}}$ and $\phi_{\mathrm{R}_{\mathcal{S}i}}$ respectively denote the RX amplitude and phase mismatch

- Received signal during CE phase with joint TX and RX IQI is given by

$$\mathbf{Y}_{\mathrm{JI}} = \mathbf{H}_{\mathrm{A}}\,\mathbf{S}_{\mathrm{p}} + \left(\mathbf{R}_{\mathcal{S}1}\,\mathbf{H}\,\mathbf{T}_{\mathcal{U}2} + \mathbf{R}_{\mathcal{S}2}\,\mathbf{H}^{*}\,\mathbf{T}_{\mathcal{U}1}^{*}\right)\mathbf{S}_{\mathrm{p}}^{*} + \mathbf{W}_{\mathrm{JI}}, \tag{3}$$

where $\mathbf{H}_{\mathrm{A}} \triangleq \mathbf{R}_{\mathcal{S}1}\,\mathbf{H}\,\mathbf{T}_{\mathcal{U}1} + \mathbf{R}_{\mathcal{S}2}\,\mathbf{H}^{*}\,\mathbf{T}_{\mathcal{U}2}^{*}$ and $\mathbf{W}_{\mathrm{JI}} \triangleq \mathbf{R}_{\mathcal{S}1}\,\mathbf{W} + \mathbf{R}_{\mathcal{S}2}\,\mathbf{W}^{*}$

- Frequency-independent IQI as narrow band signals in WPT and UL CE
- Limited feedback at $\mathcal{S}$ from energy-constrained $\boldsymbol{\mathcal{U}} \rightarrow$ **no** IQI compensation
- 2nd and 3rd terms in (3) represent interference and scaled noise due to IQI

Uplink Channel Estimation under TX-RX IQI

- The LS estimate $\widehat{\mathbf{H}}_{\mathrm{A_L}} \in \mathbb{C}^{N\times M}$ for the effective channel $\mathbf{H}_{\mathrm{A}}$ under IQI is

$$\widehat{\mathbf{H}}_{\mathrm{A_L}} = \mathbf{Y}_{\mathrm{JI}}\,\mathbf{S}_{\mathrm{p}}^{\mathrm{H}}\left(\mathbf{S}_{\mathrm{p}}\,\mathbf{S}_{\mathrm{p}}^{\mathrm{H}}\right)^{-1} = \mathbf{Y}_{\mathrm{JI}}\,\mathbf{S}_{\mathrm{p}}^{\mathrm{H}}\,(p_c\tau_c)^{-1}, \tag{4}$$

where p_c and τ_c represent the time and power allocation during CE

- LMMSE can provide more accurate CE if CSI statistics known *a priori*
- LMMSE estimate $\widehat{\mathbf{H}}_{\mathrm{A_M}} \in \mathbb{C}^{N\times M}$ for $\mathbf{H}_{\mathrm{A}}$ can be obtained as

$$\widehat{\mathbf{H}}_{\mathrm{A_M}} = \boldsymbol{\mu}_{\mathbf{H}_{\mathrm{A}}} + \mathbf{C}_{\mathbf{H}_{\mathrm{A}},\mathbf{Y}_{\mathrm{JI}}}\left(\mathbf{C}_{\mathbf{Y}_{\mathrm{JI}}}\right)^{-1}\left(\mathbf{Y}_{\mathrm{JI}} - \boldsymbol{\mu}_{\mathbf{Y}_{\mathrm{JI}}}\right), \tag{5}$$

where $\boldsymbol{\mu}$ and $\mathbf{C}$ are used to respectively denote the means and covariances

Downlink Wireless RF Power Transfer

Ideal Scenario: Perfect CSI with No IQI:

- To maximize this sum harvested power P_H among M EH users, with perfect CSI available at $\mathcal{S}$ and no IQI, the optimal TX precoding is

$$\mathbf{x}_{\mathrm{opt}} = \sqrt{p_e}\,\mathbf{v}_{max}\left(\mathbf{H}^{*}\,\mathbf{H}^{\mathrm{T}}\right), \tag{6}$$

with p_e as DL TX power and $\mathbf{v}_{max}\left(\mathbf{H}^{*}\,\mathbf{H}^{\mathrm{T}}\right) \in \mathbb{C}^{N\times 1}$ representing the eigenvector corresponding to largest eigenvalue $\lambda_{max}\left(\mathbf{H}^{*}\,\mathbf{H}^{\mathrm{T}}\right)$ of $\mathbf{H}^{*}\,\mathbf{H}^{\mathrm{T}}$.

- Maximum sum harvested DC power $P_{H_{\mathrm{opt}}}$ under this ideal scenario is

$$P_{H_{\mathrm{opt}}} = \eta\, p_e\, \lambda_{max}\left(\mathbf{H}^{*}\,\mathbf{H}^{\mathrm{T}}\right), \tag{7}$$

where $\eta\left(\cdot\right)$ represents the nonlinear RF-to-DC rectification efficiency [7]

DL WPT under IQI and CE errors

- Received energy signal at $\boldsymbol{\mathcal{U}}$ during DL WPT under TX IQI (i.e., $\mathcal{S}$-IQI):

$$\mathbf{y}_{\mathrm{eTI}} = \mathbf{H}^{\mathrm{T}}\left(\mathbf{T}_{\mathcal{S}1}\,\mathbf{x} + \mathbf{T}_{\mathcal{S}2}\,\mathbf{x}^{*}\right) + \mathbf{w}_{\mathcal{U}}. \tag{8}$$

Here $\mathbf{w}_{\mathcal{U}}$ is AWGN, $g_{\mathrm{T}_{\mathcal{S}i}}$ and $\phi_{\mathrm{T}_{\mathcal{S}i}}$ in ith diagonal entries $[\mathbf{T}_{\mathcal{S}1}]_i \triangleq \frac{1+g_{\mathrm{T}_{\mathcal{S}i}} \mathrm{e}^{j\phi_{\mathrm{T}_{\mathcal{S}i}}}}{2}$ and $[\mathbf{T}_{\mathcal{S}2}]_i \triangleq \frac{1}{2}\left(1 - g_{\mathrm{T}_{\mathcal{S}i}} \mathrm{e}^{j\phi_{\mathrm{T}_{\mathcal{S}i}}}\right)$ respectively denote the TX amplitude and phase mismatch at the ith antenna at $\mathcal{S}$ during DL WPT to $\boldsymbol{\mathcal{U}}$

- WPT does not suffer from the RX IQI in DL (or $\boldsymbol{\mathcal{U}}$-IQI) because RF EH does not require the RF to baseband conversion that may suffer IQI
- $\boldsymbol{\mathcal{U}}$-IQI affects UL CE, whereas $\mathcal{S}$-IQI affects both UL CE and DL WPT

Harvested Power among EH Users under IQI and CE Errors

Using the channel estimate, LS $\widehat{\mathbf{H}}_{\mathrm{A_L}}$ or LMMSE $\widehat{\mathbf{H}}_{\mathrm{A_M}}$, along with (6), the optimal TX precoding under IQI and CE errors is given by

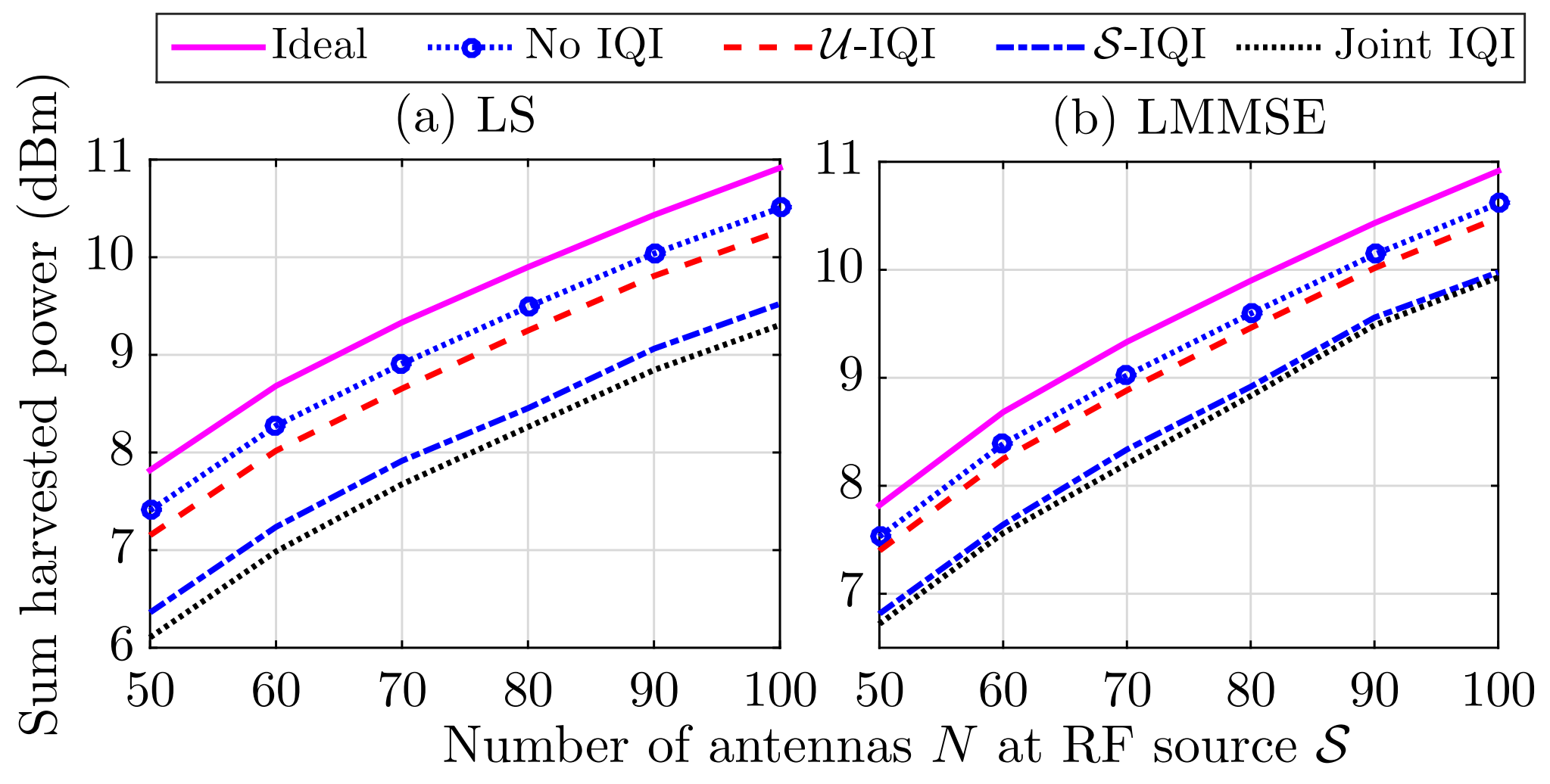
$$\mathbf{x}_{\widehat{\mathbf{H}}_{\mathrm{A_E}}} = \sqrt{p_e}\,\mathbf{v}_{max}\left(\widehat{\mathbf{H}}_{\mathrm{A_E}}^{*}\,\widehat{\mathbf{H}}_{\mathrm{A_E}}^{\mathrm{T}}\right),\ \forall\,\mathrm{E} = \{\mathrm{L}, \mathrm{M}\}, \tag{9}$$

and the corresponding sum harvested DC power $P_{\widehat{\mathbf{H}}_{\mathrm{A_E}}}$ is derived as

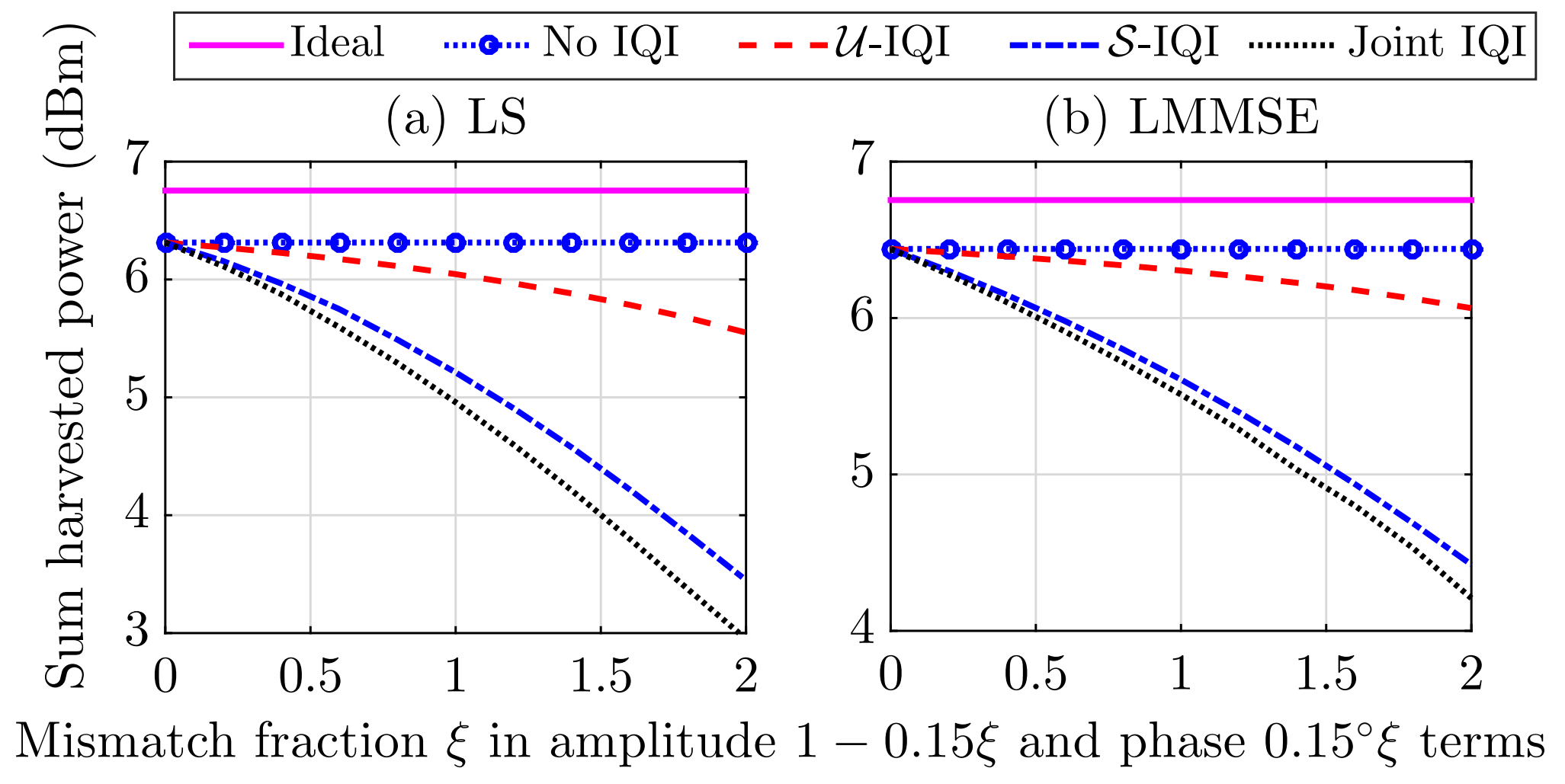
$$P_{\widehat{\mathbf{H}}_{\mathrm{A_E}}} = \eta\,\mathrm{tr}\left(\mathbf{y}_{\mathrm{eTI}}\,\mathbf{y}_{\mathrm{eTI}}^{\mathrm{H}}\right) = \eta\,\mathrm{tr}\left(\mathbf{H}^{\mathrm{T}}\left(\mathbf{T}_{\mathcal{S}1}\,\mathbf{x}_{\widehat{\mathbf{H}}_{\mathrm{A_E}}} + \mathbf{T}_{\mathcal{S}2}\,\mathbf{x}_{\widehat{\mathbf{H}}_{\mathrm{A_E}}}^{*}\right)\left(\mathbf{x}_{\widehat{\mathbf{H}}_{\mathrm{A_E}}}^{\mathrm{H}}\,\mathbf{T}_{\mathcal{S}1}^{\mathrm{H}} + \mathbf{x}_{\widehat{\mathbf{H}}_{\mathrm{A_E}}}^{\mathrm{T}}\,\mathbf{T}_{\mathcal{S}2}^{\mathrm{H}}\right)\mathbf{H}^{*}\right),\ \forall\,\mathrm{E} = \{\mathrm{L}, \mathrm{M}\} \tag{10}$$

- Under $\mathcal{S}$-IQI alone, $\mathbf{T}_{\mathcal{U}1} = \mathbf{I}_M$ and $\mathbf{T}_{\mathcal{U}2} = \mathbf{0}_{M\times M}$ in (10)
- Under $\boldsymbol{\mathcal{U}}$-IQI alone, $\mathbf{R}_{\mathcal{S}1} = \mathbf{T}_{\mathcal{S}1} = \mathbf{I}_N$ and $\mathbf{R}_{\mathcal{S}2} = \mathbf{T}_{\mathcal{S}2} = \mathbf{0}_{N\times N}$ in (10)
- We compare the performances of $\mathcal{S}$-IQI and $\boldsymbol{\mathcal{U}}$-IQI alone with joint IQI

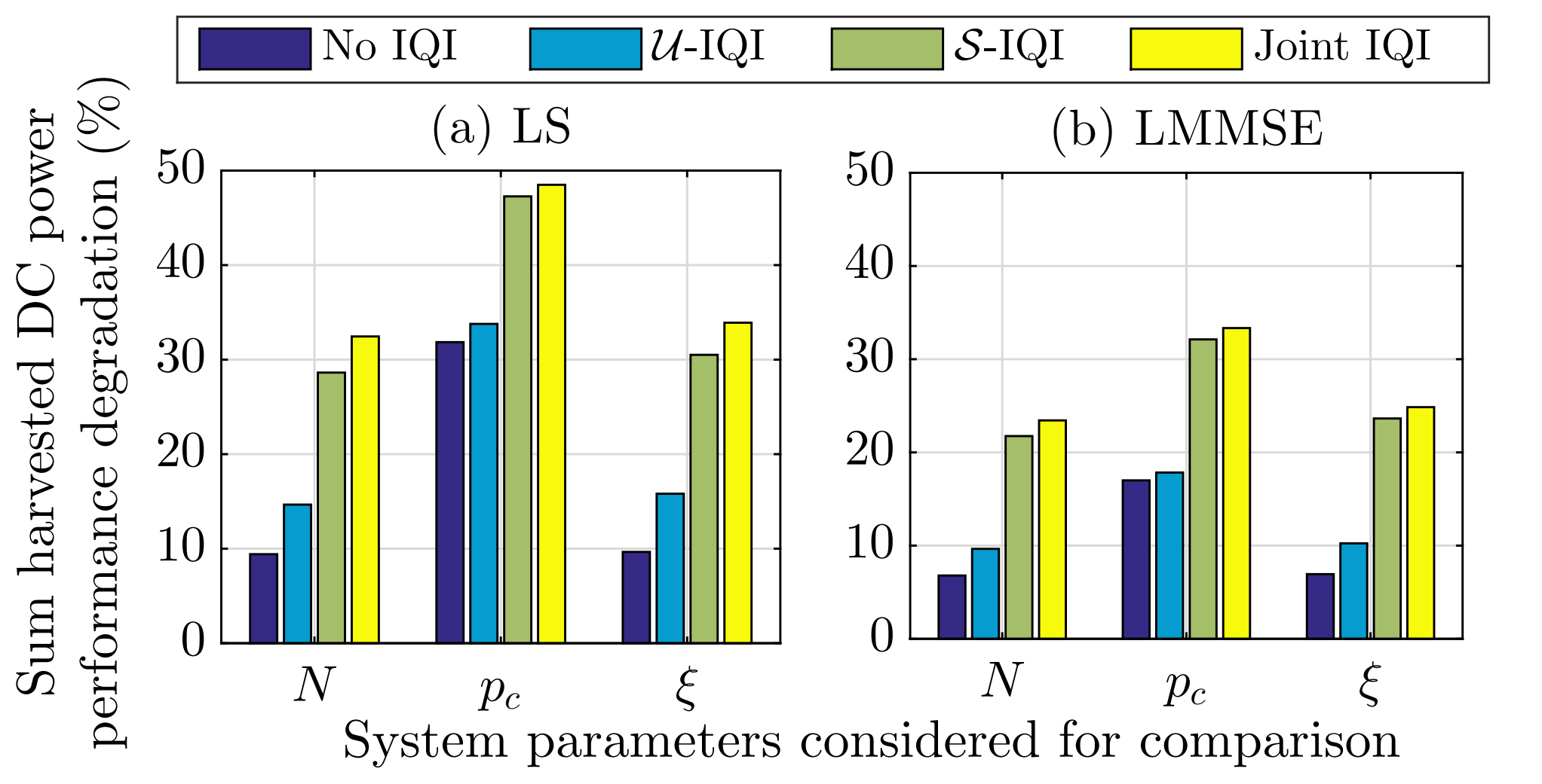
Numerical Results



- Quantify sum harvested power among users
- Five cases: 1. 'ideal' (perfect CSI with no IQI), 2. No IQI (only CE errors), 3. users $\boldsymbol{\mathcal{U}}$-IQI, 4. RF source $\mathcal{S}$-IQI, 5. Joint IQI
- $\boldsymbol{\mathcal{U}}$-IQI is a relatively *minor concern*
- $\mathcal{S}$-IQI affecting both UL CE and DL WPT has a more significant impact
- Degradation in EH increases with N



- Identical IQI assumed for each RF chain
- Amplitude: $1 - 0.15\xi$, Phase: $15°\xi$
- Performance degrades with mismatch ξ
- Degradation more prominent in LS-CE
- Mismatch ξ from $0 \rightarrow 2$, leads to about 54% & 38% decrease in EH performance due to joint IQI as compared to no IQI for LS & LMMSE based CE, respectively



- Sum EH degradation is much higher for the LS based CE compared to LMMSE
- IQI and CE errors jointly can lead to about 30% degradation in achievable gains
- $\boldsymbol{\mathcal{U}}$-IQI being a minor concern, enables to have cheaper hardware at EH-IoT nodes
- More than 18% degradation in sum EH due to IQI alone without any CE errors

Concluding Remark

As IQI may cause significant EH performance degradation than CE errors alone, it needs to be compensated at massive antenna source for realizing the full energy beamforming gains

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