# Channel Estimation and Low-Complexity Beamforming Design for Passive Intelligent Surface Assisted MISO Wireless Energy Transfer

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## Introduction and Background

### Passive intelligent surface (PIS) assisted sustainable communications

- Elements in an active array [1] have costly dedicated radio frequency (RF) chains
- PIS being low-cost green alternative have been used for radar and space communications
- Each passive element can be a low-cost printed dipole, integrated into walls
- Potential in supporting high data rate and energy sustainability demands of 5G networks

### State of the art

- Active intelligent surface based massive MISO communications for indoor applications [2]
- Optimal power allocation and PIS phase shifters (PS) design to maximize sum-rate [3]
- PIS-assisted energy transfer (PET) to an energy harvesting (EH) user using semidefinite relaxation (SDR) based optimal active and passive energy beamforming (EB) design [4],

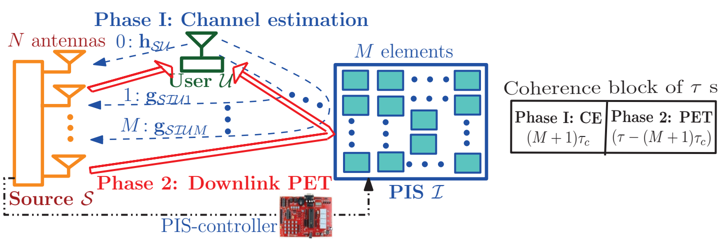
### Motivation

- Existing investigations assumed perfect channel state information (CSI) availability
- No channel estimation (CE) protocol available considering radio resource-limited PIS
- Proposed PIS-limitations-aware EB designs can be applied to both energy transfer and information decoding systems demanding perpetual connectivity for internet-of-things

## Key Contribution

- Novel robust CE protocol for multiantenna PET to EH user without PIS-feedback
- Near-optimal closed-forms for both transmit (active) and reflect (passive) EB designs

## System Description




- Point-to-point MISO system consisting of $N$-antenna power beacon (PB), or source $\mathcal{S}$, serving a single-antenna EH user $\mathcal{U}$ over flat quasi-static Rician block fading channels
- A PIS $\mathcal{I}$ comprising $M$ passive elements is installed on the opposite wall near $\mathcal{S}$
- With $\alpha_i \in (0,1)$ and $\theta_i \in (0, 2\pi)$ denoting amplitude reflection coefficient and PS value for the $i$th element of PIS, the diagonal PS matrix representing passive EB design is

$$\mathbf{\Theta} \triangleq \text{diag}\left\{\alpha_1 e^{j\theta_1}\ \alpha_2 e^{j\theta_2} \ldots \alpha_M e^{j\theta_M}\right\} \in \mathbb{C}^{M\times M}.$$

- PIS-controller of $\mathcal{I}$ is an ultra-low-power micro-controller programmed by PB which can dynamically adjust values of $\{\alpha_i\}$ and $\{\theta_i\}$ to orient reflections in the desired directions

## Proposed Channel EstimationProtocol

- Each coherence block of $\tau$ s is divided into subphases: (i) uplink CE, (ii) downlink PET
- Binary-reflection (*full* or *no*) controlled least-squares (LS) CE protocol of $(M+1)\,\tau_c$ is proposed to obtain LS estimator (LSE) for $M+1$ channel, having $N$ elements each, as denoted by $\mathbf{h}_{\mathcal{SU}}$ and $M$ columns $\{\mathbf{g}_{\mathcal{SIU}i}\}$ of cascaded channel $\mathbf{G}_{\mathcal{SIU}} \triangleq \mathbf{H}_{\mathcal{SI}}\,\text{diag}\left\{\mathbf{h}_{\mathcal{IU}}^{\mathrm{T}}\right\}$
- As PIS $\mathcal{I}$ has no active radio components, PB estimates all these $M+1$ channel vectors
- During CE subphase $i$ of duration $\tau_c$, only $i$th passive element is in *full-reflection* mode
- Non-negative constants $\epsilon_1$ and $\epsilon_0$ respectively modeling these realistic implementation errors in *ON* and *OFF* modes, entries of combined $\mathcal{I}$'s PS matrix during CE phase are:

$$[\mathbf{\Phi}]_{i,m} \triangleq \begin{cases} 1-\epsilon_1, & (i=m)\wedge(m\neq 1) \\ 0+\epsilon_0, & (i\neq m)\vee(m=1) \end{cases}, \quad \forall\, 1\leq i\leq M, 1\leq m\leq M+1$$

- With $x_p$ being pilot having power $p_c$ from $\mathcal{U}$, received signal matrix at $\mathcal{S}$ during CE is

$$\mathbf{Y}_{\mathcal{S}} = \left(\left(\left(\mathbf{h}_{\mathcal{SU}} \otimes \mathbf{1}_{1\times(M+1)}\right) + \mathbf{G}_{\mathcal{SIU}}\,\mathbf{\Phi}\right) \otimes x_p\right) + \mathbf{W}_{\mathcal{S}}.$$

- Writing $\mathbf{Y}_{\mathcal{S}} = \left[\mathbf{y}_1\ \overline{\mathbf{Y}}_{\mathcal{S}}\right]$, noise $\mathbf{W}_{\mathcal{S}} = \left[\mathbf{w}_1\ \overline{\mathbf{W}}_{\mathcal{S}}\right]$, $\mathbf{\Phi} = \left[\epsilon_0 \mathbf{1}_{M\times 1}\ \ \overline{\mathbf{\Phi}}\right]$, and $\mathbf{X}_p \triangleq \overline{\mathbf{\Phi}} \otimes x_p$, the LSE of $\mathcal{S}$-to-$\mathcal{U}$ channel $\mathbf{h}_{\mathcal{SU}}$ as obtained using the pseudoinverse $x_p^{\dagger} \triangleq \frac{x_p^*}{p_c \tau_c}$ of $x_p$ is

$$\widehat{\mathbf{h}}_{\mathcal{SU}} = \mathbf{y}_1 x_p^{\dagger} = \mathbf{h}_{\mathcal{SU}} + \widehat{\mathbf{h}}_{\mathcal{SU}} - \mathbf{h}_{\mathcal{SU}} = \epsilon_0\, \mathbf{G}_{\mathcal{SIU}}\, \mathbf{1}_{M\times 1} + \mathbf{w}_1\, x_p^* \left(p_c\, \tau_c\right)^{-1}$$

- Using this LSE $\widehat{\mathbf{h}}_{\mathcal{SU}}$ of $\mathbf{h}_{\mathcal{SU}}$, the LSE for cascaded channel matrix $\mathbf{G}_{\mathcal{SIU}}$ is obtained as

$$\widehat{\mathbf{G}}_{\mathcal{SIU}} = \left(\overline{\mathbf{Y}}_{\mathcal{S}} - x_p\left(\widehat{\mathbf{h}}_{\mathcal{SU}} \otimes \mathbf{1}_{1\times M}\right)\right) \mathbf{X}_p^{\mathrm{H}} \left(\mathbf{X}_p \mathbf{X}_p^{\mathrm{H}}\right)^{-1}$$

## Jointly Optimal Active and Passive EB Design

- Assuming no CE errors at $\mathcal{S}$, EB for received power maximization at $\mathcal{U}$ is formulated as

$$\mathcal{O}_{\mathrm{J}}: \max_{\mathbf{f}_{\mathrm{A}}, \mathbf{f}_{\mathrm{P}}}\ \mathcal{P}_{\mathcal{U}} \triangleq p_e \left|\left(\mathbf{h}_{\mathcal{SU}}^{\mathrm{T}} + \mathbf{f}_{\mathrm{P}}^{\mathrm{T}}\, \mathbf{G}_{\mathcal{SIU}}^{\mathrm{T}}\right) \mathbf{f}_{\mathrm{A}}\right|^2, \ \text{s. t. } (\mathrm{C1}): \|\mathbf{f}_{\mathrm{A}}\|^2 \leq 1,\ (\mathrm{C2}): |[\mathbf{f}_{\mathrm{P}}]_i| = 1, \forall i$$

  where $\mathbf{f}_{\mathrm{A}} \in \mathbb{C}^{N\times 1}$ is unit-norm linear precoder or active EB vector at $\mathcal{S}$ and passive EB or PS vector $\mathbf{f}_{\mathrm{P}} \in \mathbb{C}^{M\times 1}$ at $\mathcal{I}$ or PIS represents the $M$ diagonal entries of $\mathbf{\Theta}$
- Benchmark work [4] has proposed maximum ratio transmission (MRT) for active EB vector $\mathbf{f}_{\mathrm{A}}$ as $\mathbf{f}_{\mathrm{A}_{\mathrm{opt}}^{\mathrm{id}}} = \frac{\mathbf{h}_{\mathcal{SU}}^* + \mathbf{G}_{\mathcal{SIU}}^* \mathbf{f}_{\mathrm{P}}^*}{\left\|\mathbf{h}_{\mathcal{SU}}^* + \mathbf{G}_{\mathcal{SIU}}^* \mathbf{f}_{\mathrm{P}}^*\right\|}$ at $\mathcal{S}$ with SDR-based solution for passive EB $\mathbf{f}_{\mathrm{P}}$
- Complexity of existing design [4] with $M+1$ variables and constraints is: $O\left((M+1)^6\right)$
- Adopting MRT for active EB design, the received RF power at $\mathcal{U}$ can be rewritten as

$$\mathcal{P}_{\mathcal{U}_{\mathrm{A}}^{\mathrm{opt}}} = p_e \left\|\mathbf{h}_{\mathcal{SU}}^{\mathrm{T}} + \mathbf{f}_{\mathrm{P}}^{\mathrm{T}}\, \mathbf{G}_{\mathcal{SIU}}^{\mathrm{T}}\right\|^2 = p_e \left(\left\|\mathbf{h}_{\mathcal{SU}}^{\mathrm{T}}\right\|^2 + \left\|\mathbf{f}_{\mathrm{P}}^{\mathrm{T}}\, \mathbf{G}_{\mathcal{SIU}}^{\mathrm{T}}\right\|^2 + 2\left\langle \mathbf{h}_{\mathcal{SU}}^{\mathrm{T}}, \mathbf{f}_{\mathrm{P}}^{\mathrm{T}}\, \mathbf{G}_{\mathcal{SIU}}^{\mathrm{T}}\right\rangle\right),$$

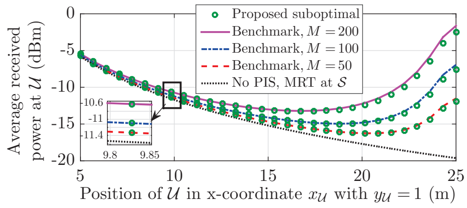
- To ensure reflected signals from $\mathcal{I}$ get coherently added at $\mathcal{U}$ with ones received directly from $\mathcal{S}$, analytical expression for proposed passive EB is: $\mathbf{f}_{\mathrm{P}_{\mathrm{opt}}^{\mathrm{id}}} = \exp\left\{-j \angle \mathbf{G}_{\mathcal{SIU}}^{\mathrm{T}}\, \mathbf{h}_{\mathcal{SU}}^*\right\}$
- Thus, practical joint active and passive EB designs using LSE for $\mathbf{h}_{\mathcal{SU}}$ and $\mathbf{G}_{\mathcal{SIU}}$ are

$$\mathbf{f}_{\mathrm{A}_{\mathrm{opt}}^{\mathrm{pra}}} \triangleq \frac{\widehat{\mathbf{h}}_{\mathcal{SU}}^* + \widehat{\mathbf{G}}_{\mathcal{SIU}}^*\, \mathbf{f}_{\mathrm{P}_{\mathrm{opt}}^{\mathrm{pra}}}^*}{\left\|\widehat{\mathbf{h}}_{\mathcal{SU}}^* + \widehat{\mathbf{G}}_{\mathcal{SIU}}^*\, \mathbf{f}_{\mathrm{P}_{\mathrm{opt}}^{\mathrm{pra}}}^*\right\|} \quad \text{and} \quad \mathbf{f}_{\mathrm{P}_{\mathrm{opt}}^{\mathrm{pra}}} \triangleq \exp\left\{-j \angle \widehat{\mathbf{G}}_{\mathcal{SIU}}^{\mathrm{T}}\, \widehat{\mathbf{h}}_{\mathcal{SU}}^*\right\}$$

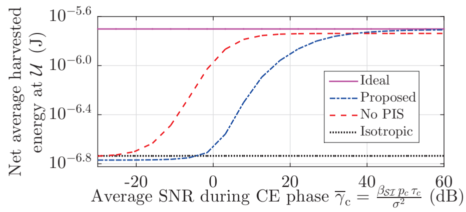
## Numerical Results

- **Parameters**: $N = 10, M = 20$, $\tau = 1\text{ms}$, $\tau_c = \frac{0.01\tau}{M+1}$, $\epsilon_1 = 0$, $\epsilon_0 = 10^{-3}$, $p_e = 30\text{dBm}$, $p_c = -10\text{dBm}$, $\sigma_{\mathrm{w}_{\mathcal{S}}}^2 = 10^{-20}$ Joule (J), $\eta = 0.7, K_{\mathcal{SU}} = K_{\mathcal{IU}} = 0$, $K_{\mathcal{SI}} = 10, \delta = \frac{3\times 10^8}{2f}$, $\beta_{ik} = \frac{G_i G_k \varpi}{d_{ik}^{\varrho}}, \forall i,k \in \{\mathcal{S},\mathcal{U},\mathcal{I}\}$, $\varpi = \left(\frac{\delta}{2\pi}\right)^2$, $G_{\mathcal{S}} = G_{\mathcal{U}} = 0\text{dBi}$, $G_{\mathcal{I}} = 5\text{dBi}$ [4], $\varrho = 2$

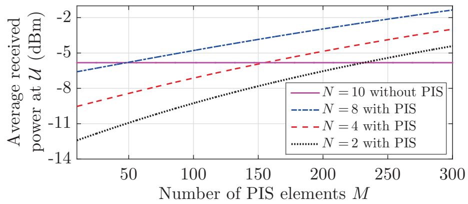
- EH performance gap between benchmark and our closed-form design is $\leq 3.5\%$ for $M \leq 200$
- Proposed EB designs for PET with $M = 100$ provides 4.1dB improvement over *No PIS* case



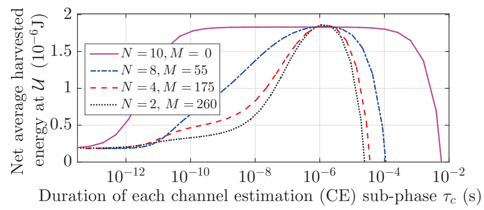

- Goodness of LSEs is validated
- For SNRs $\geq$ 45dB, performance with proposed LSE approaches that of perfect CSI availability
- CE accuracy is more critical in PET as compared to *No PIS*




- Selecting PIS size $M$ to achieve the same EB gain with lower $N$
- To reduce 6 antennas in $N = 10$ and $N = 8$ designs, we need 163 and 187 extra PIS elements
- When $\mathcal{U}$ moves closer to PIS, fewer passive elements $M$ for reducing active array size $N$




- Average harvested energy is unimodal in $\tau_c$ with optimal CE time as $\frac{\tau}{1000}$, regardless of $N, M$
- Due to CE errors, 8% more passive elements are required to reduce $N$ when using LSEs




## Concluding Remark

Setting CE time as $\tau_c \approx \frac{\tau}{1000}$, a larger-sized low-cost PIS can be chosen to have smaller active array size at PB to implement EB in an efficient way while using proposed LSE

## Selected References

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[3] C. Huang, A. Zappone, M. Debbah, and C. Yuen, "Achievable rate maximization by passive intelligent mirrors," in *Proc. IEEE ICASSP*, Calgary, Canada, Apr. 2018, pp. 3714–3718.

[4] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network: Joint active and passive beamforming design," in *Proc. IEEE GLOBECOM*, Abu Dhabi, UAE, Dec. 2018, pp. 1–6.



Acknowledgment: ELLIIT