Passive Intelligent Surface Assisted MIMO Powered Sustainable IoT

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Introduction

- Passive intelligent surface (PIS):
  a) Remotely programmed via a software controller
  b) Can alter the electromagnetic behavior of the wireless channel
  c) Reflecting a phase-shifted version of the incoming signal
  d) Without requiring any active radio resource for retransmission

- Major bottlenecks include:
  a) Unawareness about the ungoverned fading channel
  b) Ultralow power computational capability

- New constant-envelope passive energy beamforming (EB) designs to gain system engineering insights

- **Focus**: Designing efficient PIS-assisted wireless energy transfer (PET) protocol

Literature Review

- Supporting timely energy sustainability demands of wireless devices in Internet-of-things (IoT) [1]

- Some of its implementation designs include:
  a) Lightweight elements attached to walls or ceilings [2]
  b) Electronically-controlled resonant frequency-based varactor diodes [3]
  c) Liquid crystal meta-surfaces fabricated via lithography or nano printing [4]

- Optimal transmit power allocation and phase shifters (PS) design for maximizing sum-rate [5]

- Statistical CSI based study on the effect of PS design on the ergodic spectral efficiency [6]

[1] 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.
[2] L. Subrt and P. Pechac, "Intelligent walls as autonomous parts of smart indoor environments," IET Commun., vol. 6, no. 8, pp. 1004–1010, May 2012.
[3] S. V. Hum and J. Perruisseau-Carrier, "Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review," IEEE Trans. Ant. Prop., vol. 62, no. 1, pp. 183–198, Jan. 2014.
[4] S. Foo, "Liquid-crystal reconfigurable metasurface reflectors," in Proc. IEEE Int. Symp. on Ant. Prop. (ISAP), San Diego, USA, July 2017, pp. 2069–2070.
[5] 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.
[6] Y. Han, W. Tang, S. Jin, C. Wen, and X. Ma, "Large intelligent surface-assisted wireless communication exploiting statistical csi," IEEE Trans. Veh. Tech., vol. 68, no. 8, pp. 8238–8242, Aug. 2019.

Multiuser Designs and Research Gap

- SDR and alternating optimization techniques to obtain passive EB designs for PIS-assisted multiuser MISO [7]
- Likewise, two alternating optimization-based efficient energy efficiency maximization algorithms [8]
- Joint active and passive beamforming using random matrix theory tools for max-min goal [9]

- Concerns with existing designs:
  a) Low-complexity constraints of PIS were ignored
  b) Perfect CSI availability was assumed
- Compressive sensing-based channel construct approach to obtain the full CSI [10]
- Least-squares (LS) based channel estimation (CE) protocol for single-user setting [11].

- **Research Gap**: Multiuser CE protocol involving low-complexity EB designs for maximizing sum power during PET

[7] Q. Wu and R. Zhang, “Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming,” IEEE Trans. Wireless Commun., vol. 18, no. 11, pp. 5394-5409, Nov. 2019.
[8] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, “Reconfigurable intelligent surfaces for energy efficiency in wireless communication,” IEEE Tran. Wireless Commun., vol. 18, no. 8, pp. 4157–4170, Aug. 2019.
[9] Q.-U.-A. Nadeem, A. Kammoun, A. Chaaban, M. Debbah, and M.-S. Alouin, “Asymptotic analysis of large intelligent surface assisted MIMO communication,” arXiv:1903.0812, Apr. 2019.
[10] C. Liaskos, A. Tsioliaridou, A. Pitilakis, G. Pirialakos, O. Tsilipakos, A. Tasolamprou, N. Kantartzis, S. Ioannidis, M. Kafesaki, A. Pitsillides, and I. Akyildiz, “Joint compressed sensing and manipulation of wireless emissions with intelligent surfaces,” in Proc. IEEE DCOSS, Santorini Island, Greece, May 2019, pp. 318–325.
[11] D. Mishra and H. Johansson, “Channel estimation and low-complexity beamforming design for passive intelligent surface assisted MISO wireless energy transfer,” in Proc. IEEE ICASSP, Brighton, UK, May 2019, pp. 4659–4663.

Motivation and Contributions

- Existing passive EB designs are based on computationally-inefficient numerical methods like SDR
- Novel analytical expressions for the jointly-optimal active and passive EB designs are needed
- Practical limitations like unavailability of strong prior for CE
- Overcoming PIS-bottlenecks by to enable sustainable IoT developing closed-form green PS designs

- The **key contribution** of this work is three-fold:

a) Novel optimization framework and LS-based CE protocol for the underlying effective cascaded channels to maximize the sum power
b) Closed-form expressions for optimal active precoder for power beacon (PB) and passive constant-envelope precoding-based PS design
c) Numerical investigation is carried out to validate the key analytical claims and demonstrate the performance gains over the benchmark

System Description

- **Multiuser MISO** wireless system with:
  a) L single-antenna IoT users U randomly deployed inside a square-field of length D meters (m)
  b) an N-antenna PB or energy source S
  c) an M-element PIS I installed on the opposite wall

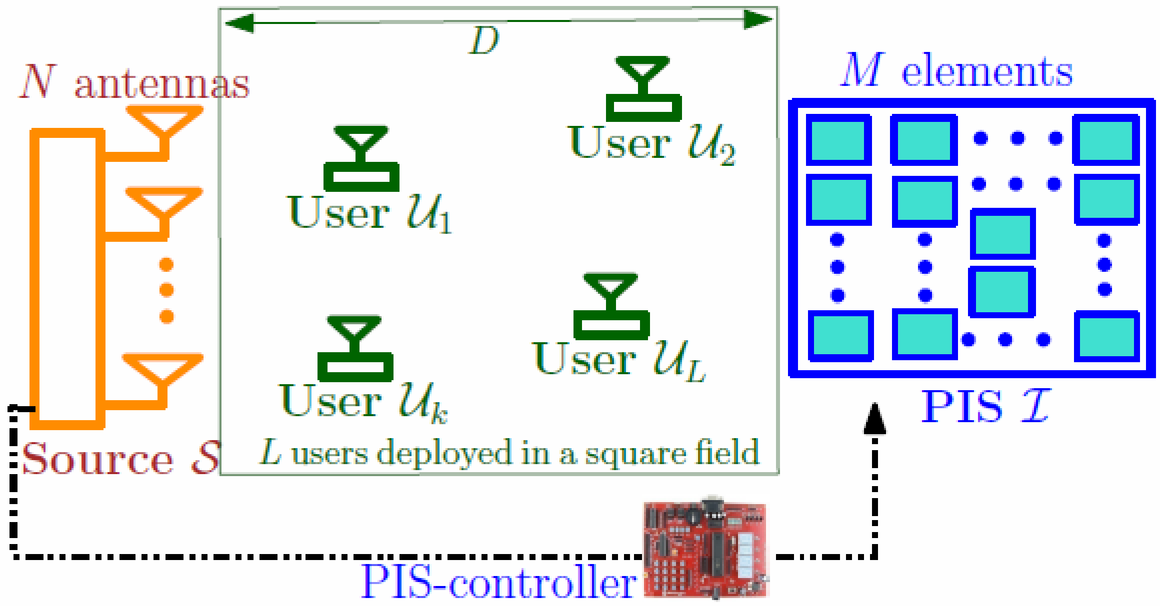
- Flat quasi-static **Rician block fading** is considered

- PIS has M dynamically reconfigurable low-resolution PS

$$\Theta \triangleq \text{diag}\left\{\alpha_1 e^{j\theta_1}\ \alpha_2 e^{j\theta_2} \ldots \alpha_M e^{j\theta_M}\right\}, \text{ with } j=\sqrt{-1}$$

- **PIS-controller** is connected and programmed by PB having all computational resources

- The composite channel involves the concatenation of S-to-I channel, PS matrix at I, and I-to-U channel



Channel-Reciprocity Based Downlink MISO PET

- Assuming channel-reciprocity, the downlink (DL) channel coefficients for all links are obtained by estimating them from the uplink (UL) pilot transmission from the IoT users

- Coherence interval is divided into **two subphases**: UL CE and DL PET

- The combined signal received at IoT users during PET subphase is:

$$\mathbf{y}_{\mathcal{U}} = \left(\mathbf{H}_{\mathcal{SU}}^{\mathrm{T}} + \mathbf{H}_{\mathcal{IU}}^{\mathrm{T}}\, \mathbf{\Theta}\, \mathbf{H}_{\mathcal{SI}}^{\mathrm{T}}\right) \mathbf{f}_{\mathrm{A}}\, x_e + \mathbf{w}_{\mathcal{U}} \;= \mathbf{G}\, \mathbf{f}_{\mathrm{A}}\, x_e + \mathbf{w}_{\mathcal{U}} \qquad \text{where } \mathbf{G} \triangleq \mathbf{H}_{\mathcal{SU}}^{\mathrm{T}} + \mathbf{H}_{\mathcal{IU}}^{\mathrm{T}} \operatorname{diag}\{\mathbf{f}_{\mathrm{P}}\}\, \mathbf{H}_{\mathcal{SI}}^{\mathrm{T}}$$

- Sum signal power as received among the L EH users can be approximated to:

$$\left\|\mathbf{y}_{\mathcal{U}}\right\|^2 \approx \mathcal{P}_{\mathcal{U}} \triangleq p_e \left\| \left(\mathbf{H}_{\mathcal{SU}}^{\mathrm{T}} + \mathbf{H}_{\mathcal{IU}}^{\mathrm{T}} \operatorname{diag}\{\mathbf{f}_{\mathrm{P}}\}\, \mathbf{H}_{\mathcal{SI}}^{\mathrm{T}}\right) \mathbf{f}_{\mathrm{A}} \right\|^2$$

On-Off PIS Design Based Channel Estimation

- Binary-reflection (on or off) based CE protocol for multiuser PET is proposed
- PB estimates the CSI for all the links on an element-by-element basis at PIS over **M + 1 subphases**
- Constants ϵ_0 and ϵ_1 model realistic implementation errors in ON and OFF modes
- The entries of the combined PS matrix during the CE phase are:

$$[\boldsymbol{\Phi}]_{i,m} \triangleq \begin{cases} 1-\epsilon_1, & i = m+1, \\ 0+\epsilon_0, & \text{otherwise}, \end{cases} \quad \forall i \in \mathcal{M},\ m \in \mathcal{M}_+, \qquad \text{where } \mathcal{M} \triangleq \{1, 2, \ldots, M\} \text{ and } \mathcal{M}_+ \triangleq \mathcal{M} \cup \{M+1\}$$

- The combined received signal matrix at S during CE can be written as:

$$\mathbf{Y}_{\mathcal{S}} = \Big(\big(\operatorname{vec}\{\mathbf{H}_{\mathcal{SU}}\mathbf{X}_p\} \otimes \mathbf{1}_{1\times(M+1)}\big) + \big((\mathbf{H}_{\mathcal{IU}}\mathbf{X}_p)^{\mathrm{T}} \otimes \mathbf{H}_{\mathcal{SI}}\big) \Big[\operatorname{diag}\Big\{\big[\boldsymbol{\Phi}^{\mathrm{T}}\big]_1\Big\} \quad \boldsymbol{\mathcal{D}}_{\Phi}\Big] \Big) + \mathbf{W}_{\mathcal{S}}$$

where $\boldsymbol{\mathcal{D}}_{\Phi} \triangleq \Big[\operatorname{diag}\Big\{\big[\boldsymbol{\Phi}^{\mathrm{T}}\big]_2\Big\}\ \operatorname{diag}\Big\{\big[\boldsymbol{\Phi}^{\mathrm{T}}\big]_3\Big\} \cdots \operatorname{diag}\Big\{\big[\boldsymbol{\Phi}^{\mathrm{T}}\big]_{M+1}\Big\}\Big]^{\mathrm{T}}$

Expressions for LS Estimates

- The vectorized form for the LS estimate of S-to-U channel matrix as obtained using the pseudo-inverse of the pilot matrix can be written as:

$$\mathrm{vec}\left\{\widehat{\mathbf{H}}_{\mathcal{SU}}\right\} = \left(\left(\mathbf{X}_{\mathrm{p}}^{\dagger}\right)^{\mathrm{T}} \otimes \mathbf{I}_N\right)\left[\mathbf{Y}_{\mathcal{S}}^{\mathrm{T}}\right]_1 = \mathrm{vec}\left\{\mathbf{H}_{\mathcal{SU}}\right\} + \epsilon_0 \mathrm{vec}\left\{\mathbf{H}_{\mathcal{SI}}\mathbf{1}_{M\times M}\mathbf{H}_{\mathcal{IU}}\right\} + \frac{\mathbf{X}_{\mathrm{p}}^{*} \otimes \mathbf{I}_N}{p_c \tau_c}\left[\mathbf{W}_{\mathcal{S}}^{\mathrm{T}}\right]_1$$

- Finally, using the LS estimate $\widehat{\mathbf{H}}_{\mathcal{SU}}$ of $\mathbf{H}_{\mathcal{SU}}$ defined, the LS estimate for the cascaded channel matrix $\boldsymbol{\mathcal{G}} \triangleq \left(\mathbf{H}_{\mathcal{IU}}^{\mathrm{T}} \otimes \mathbf{H}_{\mathcal{SI}}\right)\boldsymbol{\mathcal{D}} \in \mathbb{C}^{NL\times M}$ can be represented as:

$$\widehat{\boldsymbol{\mathcal{G}}} = \left(\left(\mathbf{X}_{\mathrm{p}}^{\dagger}\right)^{\mathrm{T}} \otimes \mathbf{I}_N\right)\left(\overline{\mathbf{Y}}_{\mathcal{S}} - \left(\mathrm{vec}\left\{\widehat{\mathbf{H}}_{\mathcal{SU}}\mathbf{X}_p\right\} \otimes \mathbf{1}_{1\times M}\right)\right)$$

$$= \left(\mathbf{H}_{\mathcal{IU}}^{\mathrm{T}} \otimes \mathbf{H}_{\mathcal{SI}}\right)\boldsymbol{\mathcal{D}}_{\Phi} + \left(\left(\mathbf{X}_{\mathrm{p}}^{\dagger}\right)^{\mathrm{T}} \otimes \mathbf{I}_N\right)\left(\overline{\mathbf{W}}_{\mathcal{S}} - \mathrm{vec}\left\{\widetilde{\mathbf{H}}_{\mathcal{SU}}\mathbf{X}_p\right\} \otimes \mathbf{1}_{1\times M}\right)$$

Optimal Active EB Design for a Given PIS Design

- Assuming perfect CSI availability at S, the joint optimization problem can be formulated as:

$$\boxed{\begin{array}{lll}\mathcal{O}_{\mathrm{J}}: \max\limits_{\mathbf{f}_{\mathrm{A}}, \mathbf{f}_{\mathrm{P}}} & \mathcal{P}_{\mathcal{U}}, & \text{subject to (s. t.)}: \\ & (\mathrm{C1}): \|\mathbf{f}_{\mathrm{A}}\|^2 \leq 1, & (\mathrm{C2}): \left|[\mathbf{f}_{\mathrm{P}}]_i\right| = 1, \forall i \in \mathcal{M}\end{array}}$$

- For a given PIS design, active EB designing problem is given by:

$$\mathcal{O}_{\mathrm{A}}: \max_{\mathbf{f}_{\mathrm{A}}} \quad \|\mathbf{G}\,\mathbf{f}_{\mathrm{A}}\|^2 = \mathrm{Tr}\left\{\mathbf{G}\,\mathbf{f}_{\mathrm{A}}\,\mathbf{f}_{\mathrm{A}}^{\mathrm{H}}\,\mathbf{G}^{\mathrm{H}}\right\}, \quad \text{s. t.} \ (\mathrm{C1})$$

- The globally-optimal solution for active EB is characterized via the principal eigenvector:

$$\mathbf{f}_{\mathrm{A}}^{\mathrm{op}} \triangleq \mathbf{v}_{\max}\left\{\mathbf{G}^{\mathrm{H}}\,\mathbf{G}\right\}$$

- The maximum value of the objective of active EB problem is bounded as:

$$\lambda_{\max}\left\{\mathbf{G}^{\mathrm{H}}\mathbf{G}\right\} \leq \|\mathbf{H}_{\mathcal{SU}}\|^2 + \|\mathbf{H}_{\mathcal{SI}}\mathrm{diag}\left\{\mathbf{f}_{\mathrm{P}}\right\}\mathbf{H}_{\mathcal{IU}}\|^2 + 2\,\mathrm{Re}\left\{\mathrm{Tr}\left\{\mathbf{H}_{\mathcal{SU}}^{\mathrm{H}}\mathbf{H}_{\mathcal{SI}}\mathrm{diag}\left\{\mathbf{f}_{\mathrm{P}}\right\}\mathbf{H}_{\mathcal{IU}}\right\}\right\}$$

PS Design Maximizing Sum Received Power via PIS

- Relaxing the nonconvex constant-envelope constraint (C2) to (C3), optimization problem reduces to:

$$\begin{aligned} \mathcal{O}_{\mathrm{P1}} : \max_{\mathrm{f_P}} \quad & \left\| \mathbf{H}_{\mathcal{SI}} \operatorname{diag}\left\{ \mathrm{f_P} \right\} \mathbf{H}_{\mathcal{IU}} \right\|^2 \\ \text{s. t.} \quad & (\mathrm{C3}) : \left\| \mathrm{f_P} \right\|^2 \le M. \end{aligned}$$

- The underlying sub-gradient Karush-Kuhn-Tucker (KKT) condition is given by:

$$\frac{\partial \mathcal{L}_{\mathrm{P1}}}{\partial \mathrm{f_P}} = \mathrm{f}_{\mathrm{P}}^{\mathrm{H}} \boldsymbol{\mathcal{D}}^{\mathrm{T}} \left(\mathbf{H}_{\mathcal{IU}}^{*} \otimes \mathbf{H}_{\mathcal{SI}}^{\mathrm{H}} \right) \left(\mathbf{H}_{\mathcal{IU}}^{\mathrm{T}} \otimes \mathbf{H}_{\mathcal{SI}} \right) \boldsymbol{\mathcal{D}} - \nu_{\mathrm{P}_1} \mathrm{f}_{\mathrm{P}}^{\mathrm{H}} = \mathbf{0}_{1 \times M}$$

- Above can be simplified to the eigenvalue problem form with underlying globally-optimal being the principal eigenvector $\mathrm{f}_{\mathrm{P}}^{\mathrm{op1}} \triangleq \mathrm{v}_{\max}\left\{ \boldsymbol{\mathcal{G}} \boldsymbol{\mathcal{G}}^{\mathrm{H}} \right\}$ of matrix $\boldsymbol{\mathcal{G}} \boldsymbol{\mathcal{G}}^{\mathrm{H}}$

- Now, as the optimal passive EB must satisfy the practical PIS design constraint (C2), the first proposed low-complexity PIS design can be obtained as the minimizer of:

$$\mathcal{O}_{\mathrm{L}} : \min_{\mathrm{f_P}} \quad \left\| \mathrm{f_P} - \mathrm{f}_{\mathrm{P}}^{\mathrm{op1}} \right\|^2, \qquad \text{s. t.} \quad (\mathrm{C2})$$

- The globally-optimal solution of above problem is: $\boxed{\mathrm{f}_{\mathrm{P}}^{\mathrm{pr1}} \triangleq \exp\left\{ j \angle \mathrm{v}_{\max}\left\{ \boldsymbol{\mathcal{G}} \boldsymbol{\mathcal{G}}^{\mathrm{H}} \right\} \right\}}$

Analytical PIS Design for Constructive Interference

- The second low-complexity PIS design is aimed to ensure that the reflected signals from PIS get coherently added up at the users with ones received directly from S

$$\mathcal{O}_{\mathrm{P}2} : \max_{\mathbf{f}_{\mathrm{P}}} \quad \mathrm{Tr}\left\{\mathbf{H}_{\mathcal{SU}}^{\mathrm{H}}\,\mathbf{H}_{\mathcal{SI}}\,\mathrm{diag}\left\{\mathbf{f}_{\mathrm{P}}\right\}\mathbf{H}_{\mathcal{IU}}\right\}, \qquad \mathrm{s.\ t.} \quad (\mathrm{C3})$$

- The sub gradient KKT condition for the above optimization problem is given by:

$$\frac{\partial \mathcal{L}_{\mathrm{P}_2}}{\partial \mathbf{f}_{\mathrm{P}}} = \left(\mathrm{vec}\left\{\mathbf{H}_{\mathcal{SU}}\right\}\right)^{\mathrm{H}}\left(\mathbf{H}_{\mathcal{IU}}^{\mathrm{T}} \otimes \mathbf{H}_{\mathcal{SI}}\right)\boldsymbol{\mathcal{D}} - \nu_{\mathrm{P}_2}\mathbf{f}_{\mathrm{P}}^{\mathrm{H}} = \mathbf{0}_{1\times M}$$

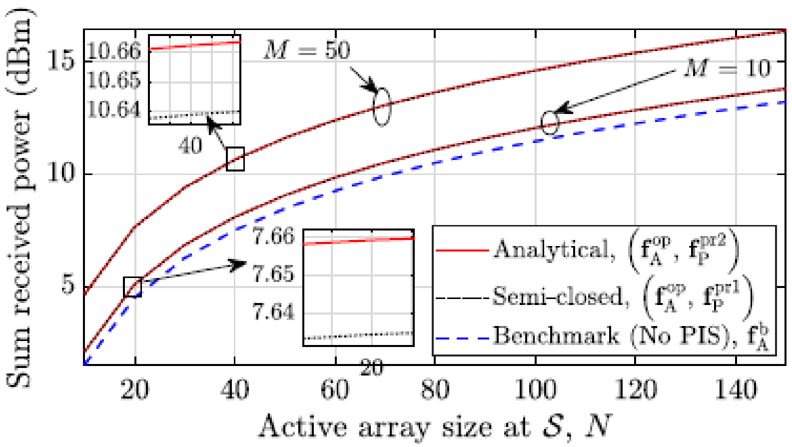
- Solving above in passive EB design leads to globally-optimal solution of the above problem as:

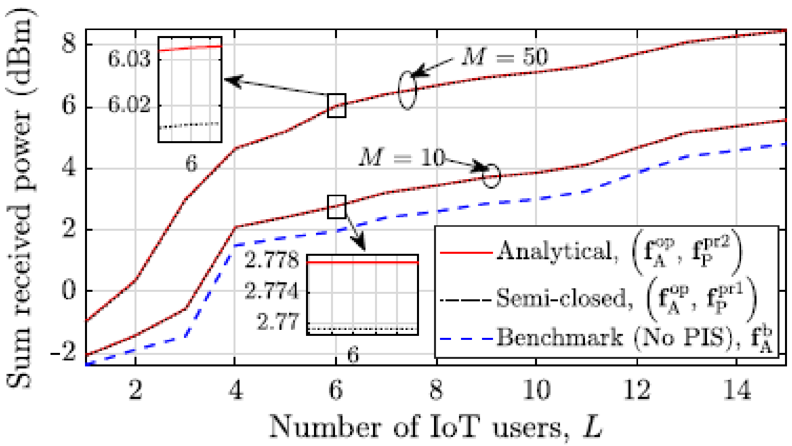
$$\mathbf{f}_{\mathrm{P}}^{\mathrm{op}2} \triangleq \frac{1}{\nu_{\mathrm{P}_2}}\,\boldsymbol{\mathcal{G}}^{\mathrm{H}}\,\mathrm{vec}\left\{\mathbf{H}_{\mathcal{SU}}\right\}$$

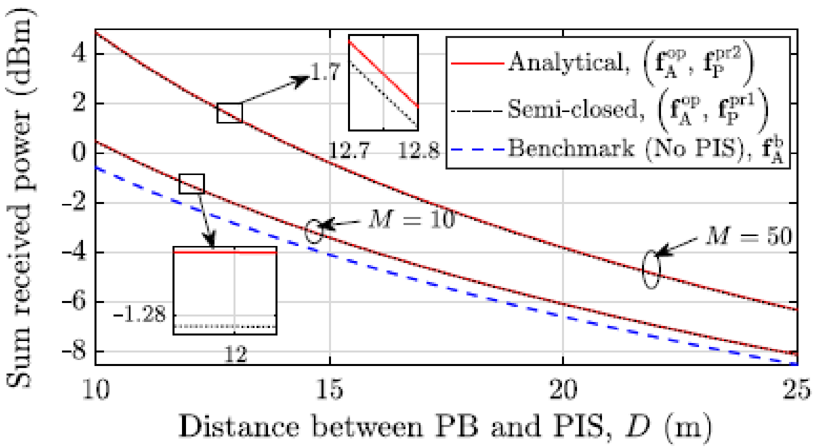
- Now again here noting that scalar ν_{P2}, the closed-form expression for the 2nd optimal constant-envelope PIS design as obtained by solving the underlying LS error minimization problem, can be written as:

$$\boxed{\mathbf{f}_{\mathrm{P}}^{\mathrm{pr}2} \triangleq \exp\left\{j\,\angle\boldsymbol{\mathcal{G}}^{\mathrm{H}}\,\mathrm{vec}\left\{\mathbf{H}_{\mathcal{SU}}\right\}\right\}}$$

Performance Comparison and Impact of Key Parameters

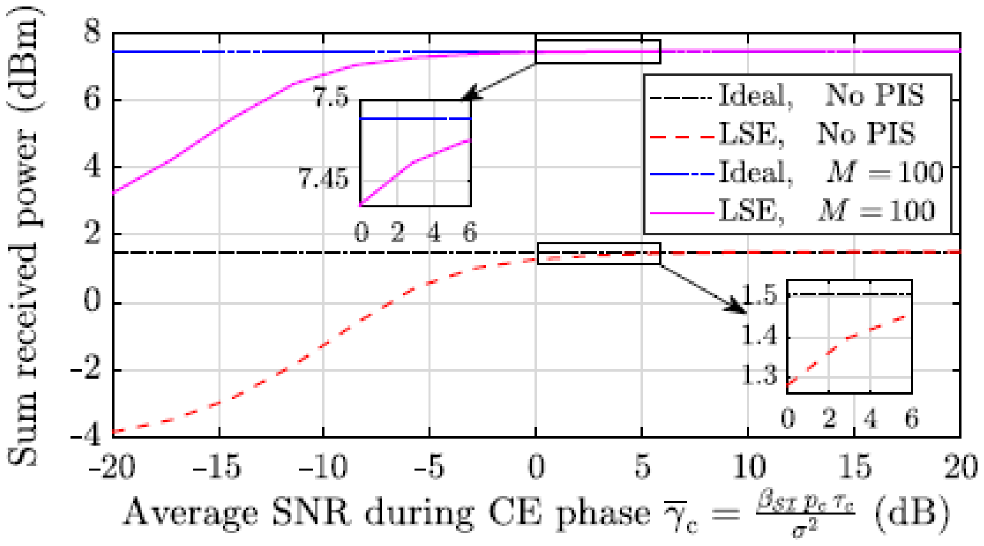


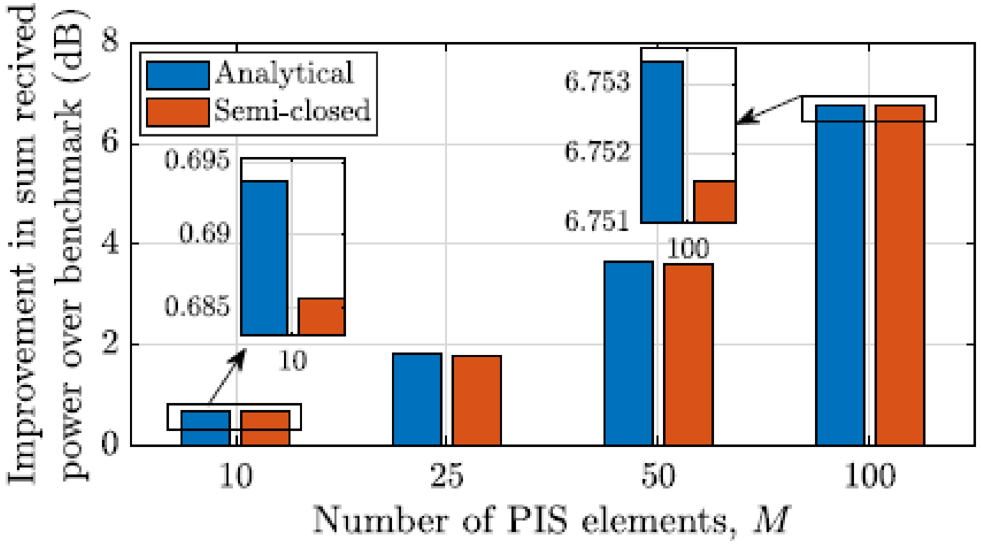




- We compare the performance of the two proposed passive EB designs (semi-closed-form and analytical PIS designs) for different values of key system parameters like active array size N at PB, PIS size M, number L of IoT users, and the distance D between PB & PIS
- The benchmark scheme considered here sets its active EB design assuming no PIS availability
- The average gain as achieved by using M = 50 over M = 10 remains almost constant around 2.6dB for varying N
- 11.7 dB gain is achieved by both schemes when N is increased from 10 to 150
- With increasing L, the sum received power performance improves by 7.65dB and 9.43dB, respectively, for M = 10 and M = 50
- With the field size D increased from 10m to 25m, the performance degrades by 4.5dB and 1.9dB, respectively, for M = 10 and M = 50

Impact of CE Errors and Gains





- The quality of the proposed estimators improves with increasing SNR for both with and without PIS settings
- For SNR higher than 5 and 10dB, the proposed estimator approaches the perfect CSI case for M = 0 and M = 100
- Analytical PIS design is better than the semi-closed-form one with a performance gap of < 0.01dB
- Using LS estimators provides an additional improvement of 0.01dB, 0.03dB, 0.06dB, and 0.13dB, for M as 10, 25, 50, and 100
- An improvement of 0.7dB to 6.8dB is achieved by the proposed CE with optimal EB for M = 10 and M = 100

Concluding Remarks

- We introduced an on-off based CE protocol for multiuser PET system
- Derived the closed-form expressions for the underlying LS estimators
- Novel analytical expressions for the jointly-optimal active and passive EB designs
- Demonstrated **significant performance enhancement** over the benchmark
- The developments can be extended for exploring the efficacy of PET in improving information rates and spectral efficiencies in multiuser systems

Thank you for your attention!

For questions and feedback, please contact:
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