Sum Throughput Maximization For Multi-Tag MISO Backscattering

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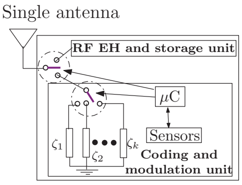
Introduction and Background

- Backscatter communication (BSC) system comprises of:
  (a) energy-rich reader (b) low-power tags

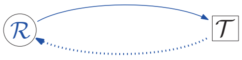


Energy harvesting tag

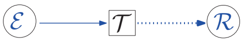
- Tag $\mathcal{T}$ relies on carrier transmission from reader $\mathcal{R}$
- $\mathcal{T}$ modulates carrier received from $\mathcal{R}$ via $x_{\mathcal{T}} \triangleq A - \zeta$
  - $A \rightarrow$, constant antenna structure
  - $\zeta \in \{\zeta_1, \zeta_2, \ldots, \zeta_V\} \rightarrow$ load-controlled backscattering coefficients (BC)
- Energy buffer based categorization of tags:
  (a) Passive (b) **Semi-passive** (c) Active
- BSC technology helps in realizing low-cost sustainable IoT
- Major **bottlenecks** → limited BSC range and low bit rate

State of the art:

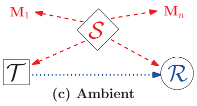
- There are three main types of BSC models:
  (a) **Monostatic** (b) Bi-static (c) Ambient
- Existing works on multiantenna reader-based multi-tag BSC:
  - Suboptimal linear transceiver designs for reader (MRC, ZF, and MMSE)
  - Transmit (TX) energy beamforming (EB) and BC designs for maximizing received energy in wireless powered communication networks (WPCN)



(a) Monostatic



(b) Bistatic



(c) Ambient

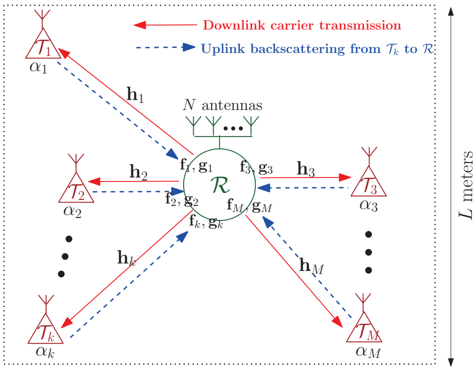
Motivation:

- Optimal transceiver design requirements at $\mathcal{R}$ in BSC are very different from those of access-points in traditional MISO settings
- Jointly-optimal multiantenna-reader and tags design has widespread utility in all BSC setups and wireless powered IoT

Key Contributions

- Novel transceiver designing at $\mathcal{R}$ and BC setting at tags to maximize sum throughput
- Efficient low-complexity jointly-optimal design using asymptotically-optimal solutions

System Description



- MISO monostatic BSC system with full-duplex N-antenna $\mathcal{R}$ and M single-antenna tags $\{\mathcal{T}_k\}$
- Linear transceiver design at $\mathcal{R}$
  - M linear precoders $\{\mathbf{f}_k \in \mathbb{C}^{N\times 1}\}$
  - M linear combiners $\{\mathbf{g}_k \in \mathbb{C}^{N\times 1}\}$
- Flat Rayleigh block fading with CSI assumed to be available at $\mathcal{R}$
- BSC channel $\{\mathbf{h}_k \sim \mathbb{CN}(\mathbf{0}, \beta_k \mathbf{I}_N)\}$
- Effective transmit signal of $\mathcal{T}_k$ is $[\mathbf{s}]_k \triangleq \frac{x_{\mathcal{T}_k}\sqrt{\alpha_k}}{|x_{\mathcal{T}_k}|}$ with α_k being BC
- With $\mathbf{w}_{\mathcal{R}} \sim \mathbb{CN}\left(\mathbf{0}, \sigma^2_{\mathrm{w}_{\mathcal{R}}} \mathbf{I}_N\right)$ being AWGN, the backscattered signal $\mathbf{y}_{\mathcal{R}} \in \mathbb{C}^{N\times 1}$ at $\mathcal{R}$ is

$$\mathbf{y}_{\mathcal{R}} \triangleq \sum_{m=1}^{m=M} \mathbf{h}_m \, [\mathbf{s}]_m \left(\mathbf{h}_m^{\mathrm{T}} \sum_{k=1}^{k=M} \mathbf{f}_k \, [\mathbf{s}_{\mathcal{R}}]_k \right) + \mathbf{w}_{\mathcal{R}}, \quad \text{with} \quad \mathbf{s}_{\mathcal{R}} \sim \mathbb{CN}(\mathbf{0}, \mathbf{I}_M)$$

Sum Throughout Maximization in BSC

- After applying linear detection on $\mathbf{y}_{\mathcal{R}}$, the backscattered-throughput R_k for $\mathcal{T}_k$ is given by

$$\mathrm{R}_k \triangleq \log_2\left(1 + \frac{\alpha_k \left|\mathbf{g}_k^{\mathrm{H}} \mathbf{h}_k\right|^2 \sum_{m\in\mathcal{M}} \left|\mathbf{h}_k^{\mathrm{T}} \mathbf{f}_m\right|^2}{\sum_{i\in\mathcal{M}}^{i\neq k} \alpha_i \left|\mathbf{g}_k^{\mathrm{H}} \mathbf{h}_i\right|^2 \sum_{m\in\mathcal{M}} \left|\mathbf{h}_i^{\mathrm{T}} \mathbf{f}_m\right|^2 + \sigma^2_{\mathrm{w}_{\mathcal{R}}} \left\|\mathbf{g}_k\right\|^2}\right), \forall k \in \mathcal{M} \triangleq \{1, \ldots, M\}$$

- The joint reader's transceiver (TRX) and tags' BC design problem can be formulated as

$$\mathcal{O}_{\mathrm{S}}: \max_{(\mathbf{f}_k, \mathbf{g}_k, \alpha_k), \forall k\in\mathcal{M}} \mathrm{R}_{\mathrm{S}} \triangleq \sum_{k\in\mathcal{M}} \mathrm{R}_k, \quad \text{subject to} \quad (\mathrm{C1}): \sum_{k\in\mathcal{M}} \|\mathbf{f}_k\|^2 \leq P_T,$$
$$(\mathrm{C2}): \|\mathbf{g}_k\|^2 \leq 1, \forall k \in \mathcal{M}, \quad (\mathrm{C3}): \alpha_k \geq \alpha_{\min}, \forall k \in \mathcal{M}, \quad (\mathrm{C4}): \alpha_k \leq \alpha_{\max}, \forall k \in \mathcal{M}$$

- $\mathcal{O}_{\mathrm{S}}$ is **nonconvex** with P_T as power budget, and ($\alpha_{\min} \geq$, $\alpha_{\max} \leq 1$) being bounds on BC
- **Lemma 1:** *Optimal TX precoders for tags, that maximize the sum backscattered throughput (SBT)* R_{S}*, are identical, i.e.,* $\mathbf{f}_k = \frac{1}{\sqrt{M}}\mathbf{f} \in \mathbb{C}^{N\times 1}, \forall k \in \mathcal{M}$

Proposed TRX and BC Design for High SNR Applications

- Under high-SNR regime, ZF-based receive (RX) beamforming is a very good design
- Defining $\mathbf{H} \triangleq [\mathbf{h}_1 \;\; \mathbf{h}_2 \;\; \mathbf{h}_3 \; \ldots \; \mathbf{h}_M]$, the optimal combiner for the high-SNR scenarios is

$$\mathbf{g}_{\mathrm{H}_k} \triangleq \frac{[\mathbf{G}_{\mathrm{Z}}]_k}{\|[\mathbf{G}_{\mathrm{Z}}]_k\|}, \quad \text{with} \quad \widetilde{\gamma}_{\mathrm{g}_k} \triangleq \left[\sigma^2_{\mathrm{w}_{\mathcal{R}}} \left\| \left[\mathbf{G}_{\mathrm{Z}}\right]_k \right\|^2\right]^{-1}, \forall k \in \mathcal{M}, \quad \text{and} \quad \mathbf{G}_{\mathrm{Z}} = \mathbf{H}\left(\mathbf{H}^{\mathrm{H}}\mathbf{H}\right)^{-1}$$

- Next using $\boldsymbol{\mathcal{F}} \triangleq \mathbf{f}\,\mathbf{f}^{\mathrm{H}}$, an equivalent semidefinite relaxation (SDR) can be formulated to maximize $\overline{\mathrm{R}}_{\mathrm{S_H}} \triangleq \sum_{k\in\mathcal{M}} \log_2\left(1 + \alpha_k \widetilde{\gamma}_{\mathrm{g}_k} \mathbf{h}_k^{\mathrm{T}} \boldsymbol{\mathcal{F}} \mathbf{h}_k^*\right)$ with $\mathrm{Tr}(\boldsymbol{\mathcal{F}}) \leq P_T, \boldsymbol{\mathcal{F}} \succeq 0$, and $\mathrm{rank}(\boldsymbol{\mathcal{F}}) = 1$
- **Lemma 2:** $\overline{\mathrm{R}}_{\mathrm{S_H}}$ *is concave in* $\boldsymbol{\mathcal{F}}$ *and increasing in BC with optimal:* $\boldsymbol{\alpha}_{\mathrm{H}} = \alpha_{\max} \mathbf{1}_{M\times 1}$
- Finally, randomization is deployed over optimal $\boldsymbol{\mathcal{F}}$ to obtain $\mathbf{f}_{\mathrm{H}}$ satisfying rank constraint

Novel TRX-BC Design Under Low SNR Scenarios in BSC

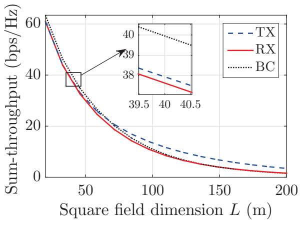
- First we notice that under low-SNR regime, R_{S} to be maximized in precoder $\mathbf{f}$ reduces to

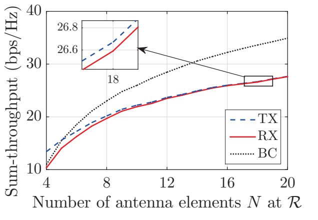
$$\mathrm{R}_{\mathrm{S_L}} = \sum_{k\in\mathcal{M}} \frac{\alpha_k \left|\mathbf{g}_k^{\mathrm{H}} \mathbf{h}_k\right|^2 \left|\mathbf{h}_k^{\mathrm{T}} \mathbf{f}\right|^2}{\ln(2)\, \sigma^2_{\mathrm{w}_{\mathcal{R}}} \|\mathbf{g}_k\|^2} \leq \frac{\alpha_{\max} \mathrm{Tr}\left\{\mathbf{H}^{\mathrm{T}} \mathbf{f}\,\mathbf{f}^{\mathrm{H}} \mathbf{H}^*\right\}}{\ln(2)\, \sigma^2_{\mathrm{w}_{\mathcal{R}}}}.$$

- So, TX precoder design $\mathbf{f}$ maximizing sum received power also yields maximum SBT
- Thus, optimal precoder, called TX-EB, is given by principal eigenvector $\mathbf{f}_{\mathrm{L}}$ of $\mathbf{H}^* \mathbf{H}^{\mathrm{T}}$
- **Lemma 3:** *With precoder as* $\mathbf{f}_{\mathrm{L}}$ *and BC as* $\alpha_{\max}$*, optimal combiner in low-SNR regime is an MMSE filter:* $\{\mathbf{g}_{\mathrm{L}_k}\} \triangleq \frac{\left(\mathbf{I}_N + \frac{P_T \alpha_{\max}}{\sigma^2_{\mathrm{w}_{\mathcal{R}}}} \sum_{i=1}^{M} \left|\mathbf{h}_i^{\mathrm{T}} \mathbf{v}_{\max}\left\{\mathbf{H}^* \mathbf{H}^{\mathrm{T}}\right\}\right|^2 \mathbf{h}_i \mathbf{h}_i^{\mathrm{H}}\right)^{-1} \mathbf{h}_k}{\left\|\left(\mathbf{I}_N + \frac{P_T \alpha_{\max}}{\sigma^2_{\mathrm{w}_{\mathcal{R}}}} \sum_{i=1}^{M} \left|\mathbf{h}_i^{\mathrm{T}} \mathbf{v}_{\max}\{\mathbf{H}^* \mathbf{H}^{\mathrm{T}}\}\right|^2 \mathbf{h}_i \mathbf{h}_i^{\mathrm{H}}\right)^{-1} \mathbf{h}_k\right\|}$
- With TRX designs obtained as $(\mathbf{f}_{\mathrm{L}}, \{\mathbf{g}_{\mathrm{L}_k}\})$, BC optimization reduces to a low-complexity binary decision-making process of selecting best BC $\boldsymbol{\alpha}_{\mathrm{L}}$ among $2^M - 1$ possible candidates

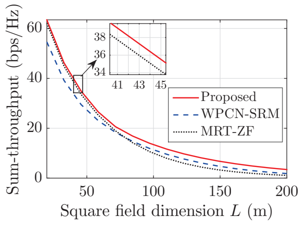
Numerical Performance Evaluation

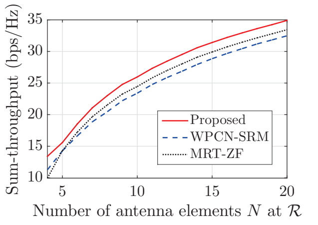
- Proposed joint TRX-BC selects **better** one between $(\mathbf{f}_{\mathrm{H}}, \{\mathbf{g}_{\mathrm{H}_k}\}, \boldsymbol{\alpha}_{\mathrm{H}})$ and $(\mathbf{f}_{\mathrm{L}}, \{\mathbf{g}_{\mathrm{L}_k}\}, \boldsymbol{\alpha}_{\mathrm{L}})$
- System parameters: $N = M = 4, P_T = 1\mathrm{W}, \sigma^2_{\mathrm{w}_{\mathcal{R}}} = 10^{-17}\mathrm{W}, \varpi = 3, L = 100\mathrm{m}\ \beta_k = \frac{\varpi}{d_k^{\varrho}}, \forall k,$ $\varpi = \left(\frac{3\times 10^8}{4\pi f}\right)^2, f = 915\mathrm{MHz}, \alpha_{\min} = 0.01$, and $\alpha_{\max} = 0.078$
- Fixed designs: precoder as $\mathbf{f}_{\mathrm{L}}$ (EB), combiner as $\mathbf{G}_{\mathrm{H}}$ (ZF) , and BC as $\boldsymbol{\alpha}_{\mathrm{H}}$ (full-reflection)
- Optimal TX precoding performs better than the other two for larger L with $N = 4$
- Optimal RX beamforming design being weakest implies that ZF is practically good
- Overall optimal BC is best semi-adaptive scheme, except under very low SNR regimes





- Benchmarks: (i) Maximizing SBT in WPCN, (ii) MRT as precoder and ZF as combiner
- Average SBT improvement of 18% and 28% is achieved over WPCN-SRM and MRT-ZF





Concluding Remarks

- Optimal precoder tradeoffs between weighted-MRT ($\mathbf{f}_{\mathrm{H}}$) and one ($\mathbf{f}_{\mathrm{L}}$) maximizing sum power at tags, while MMSE filter being optimal combiner with binary-design for BC
- Proposed closed-forms for combiner and BC designs with precoder being numerically computed using SDR and eigenvalue decomposition can provide ≈ 20% gain in SBT

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