Introduction and Background

- Backscatter communication (BSC) system comprises of:
  - (a) energy-rich reader
  - (b) low-power tags
- Tag $T$ relies on carrier transmission from reader $R$
- $T$ modulates carrier received from $R$ via $x_T = A - \zeta$
- $A$ = constant antenna structure
- $\zeta \in \mathbb{C}$ = 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 $\rightarrow$ limited BSC range and low bit rate

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

Motivation:
- Optimal transceiver design requirements at $R$ 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 design at $R$ 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 $R$ and $M$ single-antenna tags $\{T_m\}_M$
- Linear transceiver design at $R$
  - $M$ linear precoders $\{f_k \in \mathbb{C}^{N \times 1}\}$
  - $M$ linear combiners $\{g_k \in \mathbb{C}^{1 \times 1}\}$
- Flat Rayleigh block fading with CSI assumed to be available at $R$
- BSC channel $\{h_k \sim \mathcal{CN}(0, \beta I_M)\}$
- Effective transmit signal of $T_k$ is $s_{T_k} = \alpha_k h_k^\top z_{T_k}$ with $\alpha_k$ being BC
- With $w_k \sim \mathcal{CN}(0, \sigma^2_k I_K)$ being AWGN, the backscattered signal $y_k \in \mathbb{C}^{N \times 1}$ at $R$ is
  \[ y_k = \sum_{k=1}^{M} h_k^\top z_{T_k} + w_k \]
- With $s_k \sim \mathcal{CN}(0, \sigma^2_k I_M)$ being AWGN, the backscattered throughput $R_k$ for $T_k$ is given by
  \[ R_k = \log_2 \left( 1 + \frac{\alpha_k^2 \|h_k\|^2 \sum_{m=1}^{M} |f_k^\top h_m|^2}{\sum_{m=1}^{M} \|f_k^\top h_m\|^2 + \sigma^2_k \|w_k\|^2} \right) \quad \forall k \in M \Delta \{1, \ldots, M\} \]

Sum Throughput Maximization in BSC

- After applying linear detection on $y_k$, the backscattered-throughput $R_k$ for $T_k$ is given by
  \[ R_k = \log_2 \left( 1 + \frac{\alpha_k^2 \|h_k\|^2 \sum_{m=1}^{M} |f_k^\top h_m|^2}{\sum_{m=1}^{M} \|f_k^\top h_m\|^2 + \sigma^2_k \|w_k\|^2} \right) \quad \forall k \in M \Delta \{1, \ldots, M\} \]
- The joint reader’s transceiver (TRX) and tags’ BC design problem can be formulated as
  \[ \begin{align*}
  \text{maximize} & \quad \sum_{k=1}^{M} R_k \\
  \text{subject to} & \quad (C_1) \quad \sum_{k=1}^{M} |f_k|^2 \leq P_T \quad \forall k \\
  & \quad (C_2) \quad \|f_k\|_2 \leq 1, \forall k \in M \\
  & \quad (C_3) \quad \alpha_k \geq \alpha_{\text{min}}, \forall k \in M \\
  & \quad (C_4) \quad \alpha_k < \alpha_{\text{max}}, \forall k \in M \\
  \end{align*} \]
- $C_1$ is nonconvex with $P_T$ as power budget, and $(\alpha_{\text{min}} \geq \alpha_{\text{max}} \leq 1)$ being bounds on BC
- **Lemma 1**: Optimal TX precoders for tags, that maximize the sum backscattered throughput (SBT) $R_k$, are identical, i.e., $f_k = \frac{h_k^\top}{\|h_k\|^2}$, $\forall k \in M$

Proposed TRX and BC Design for High SNR Applications

- Under high-SNR regime, ZF-based receive (RX) beamforming is a very good design
- **Lemma 2**: $\max \{g_k^\top h_k^\top z_{T_k}\}$, the optimal combiner for the high-SNR scenarios is $g_k^\text{opt} \triangleq \frac{\text{argmax} \{g_k^\top h_k^\top z_{T_k}\}}{\|g_k^\top h_k^\top z_{T_k}\|}$, $\forall k \in M$, and $G_k = H_{\text{ZF}} = (H^\top H)^{-1}$
- Next using $f_k^\text{opt} \triangleq f^\top$ as an equivalent semi-definite relaxation (SDR) can be formulated to maximize $\max \{g_k^\top h_k^\top z_{T_k}\}$ with $\|f_k\|^2 \leq P_T$, $f_k^\top f_k \leq 0$, and $\|f_k\|_2 = 1$ and $\|f_k\|_2 = 1$
- **Lemma 2**: $\Pi_n$ is concave in $f_k$ and increasing in BC with optimal $\alpha_k = \alpha_{\text{max}}$ for all $k$
- Finally, randomization is deployed over optimal $f_k$ to obtain $\Pi_n$ satisfying rank constraint

Novel TRX-BC Design Under Low SNR Scenarios in BSC

- First we notice that under low-SNR regime, $R_k$ to be maximized in precoder $f_k$ reduces to
  \[ R_k = \sum_{k=1}^{M} \alpha_k h_k^\top z_{T_k} \]
- So, TX precoder design $f_k$ maximizing sum received power also yields maximum SBT
- Thus, optimal precoder, called TX-EB, is given by principal eigenvector $f_k^\text{EB}$ of $H_{\text{EB}}^\top H_{\text{EB}}$

Key Contributions

- Proposed joint TRX-BC selects better one between $f_k^\text{EB}$, $f_k^\text{ZF}$, and $f_k^\text{MMSE}$ for BC
- System parameters: $N = M = 4$, $P_T = 1W$, $\sigma^2_k = 10^{-1}W$, $\gamma = 3$, $L = 100\beta = 10^{-5}$, $\forall k$
- Fixed designs: precoder as $f_k^\text{EB}$, combiner as $g_k^\text{ZF}$ (ZF), and BC as $\alpha_k$ (full-rejection)
- Optimal TX precoding performs better than the other two for larger $N = 4$
- 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

Numerical Performance Evaluation

- Proposed joint TRX-BC selects better one between $f_k^\text{EB}$, $f_k^\text{ZF}$, and $f_k^\text{MMSE}$ for BC
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- **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 ($f_k$) and one ($f_k^\text{EB}$) maximizing sum power at tags, while MMSE filter being optimal combiner for BC
- Proposed closed-forms for combiner and BC designs with precoder being numerically computed using SDR and eigenvalue decomposition can provide $\approx 20\%$ gain in SBT

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**Sum Throughput Maximization For Multi-Tag MISO Backscattering**

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