Optimizing Backscattering Coefficient Design for Minimizing BER at Monostatic MIMO Reader

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ICASSP2020
Barcelona
Introduction

• **Multiantenna technology** can help low-power backscatter communications (BSC)

• Realizing **sustainable wireless networking** by optimally designing the detection protocols for reader [1]

• **BSC** thrives on its capability to use low-power **passive** devices like:
  a) envelope detectors,
  b) dividers,
  c) comparators,
  d) Impedance controllers and others

• Avoids **costly and bulkier** conventional RF chain components like the radio unit, local oscillator, mixer, etc

• **Challenges:** Tags in BSC do not have dedicated radio resources [2,3]

• **Focus:** Specially designed **optimal detection protocols** are needed at multiantenna readers keeping in mind the underlying channel estimation and tag signal detection **errors**


Literature Review

• Existing works on backscattering detection mostly investigated ambient BSC settings [4–5]

• Robust inference algorithms not requiring any channel statistics [6] to detect the sensing values of multiple single-antenna backscatter sensors for bistatic BSC model

• Maximum likelihood (ML) based optimal detector and suboptimal linear combiners for recovering the signals from the ambient emitter and the desired tag at the MIMO reader [7]

Monostatic BSC with MIMO Reader

- Existing works considered **perfect** channel state information (CSI) availability [8, 9] at the multiantenna monostatic reader for the maximum ratio combining (MRC) based detection [10, 11]

- Pairwise error probability and diversity order achieved by the orthogonal space-time block codes over the dyadic backscatter channel were derived in [10]

- **Research Gap:** Investigation on an optimal detection protocol for MIMO reader-based monostatic BSC

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Motivation and Contributions

- **Large antenna array at reader** for enhancing the detection performance in monostatic BSC settings
- Noting **the resource-constraints** of tags
- **Practical preamble designing** that neither requires pilot transmission from tag nor any help in channel estimation

- The **key contribution** of this work is four-fold:
  a) **Novel BSC transmission protocol** for a MIMO reader to detect the backscattered signals from a single-antenna semi-passive tag
  b) Adopting ML detector at reader, **tight analytical approximations** for the optimal detection threshold and bit error rate (BER) are derived
  c) **Globally-optimal value for tag’s backscattering coefficients** (BC) is derived in closed-form for minimizing the underlying non-convex BER
  d) The key analytical claims are **validated** via simulations, while demonstrating the **gains** achieved via optimal BC on the practical BER
Adopted Monostatic Backscattering Model

- The adopted **BSC model**:  
  a) $N_t$ antennas at reader for transmission and $N_r$ for receiving the backscattered signals  
  b) single-antenna tag

- **Uniform linear array** at the multiantenna reader

- **Rician block fading** model is adopted

- **Binary modulated backscatter design** involving amplitude shift keying between two states:  
  a) To transmit bit ‘0’, tag adjusts its impedance to move the antenna in absorbing state for ensuring that a very little fraction of incident signal is reflected to reader  
  b) For transmitting ‘1’, tag sets its impedances to ensure that the transistor is shorted and maximum amount of signal is reflected back
Three-Phase Transmission Protocol for BSC Detection

- Three-phase transmission protocol:
  a) **First phase**: \( R \) triggers \( T \) from the sleep state to get ready for backscattering.
  b) **Second phase**:
     i) After receiving \( T \)'s acknowledgment, \( R \) sends a **clearance-to-send** while following the Electronic-Product-Code Class-1 Generation-2 protocol
     ii) Reacting to it, \( T \) sends a known **preamble** sequence to aid \( R \) in estimating the long-term channel statistics like \( \sigma_h^2 \)
  c) **Third phase**: **Pilot signal transmission** from \( R \) and thereby detecting the resulting backscattered from \( T \)

- First two phases setting-up or initializing BSC and providing **estimates for statistical values** of channel parameters
- Third phase performs the **targeted ML detection**
Backscattered Signal Model

• First $N/2$ antennas for transmitting $N/2$ orthogonal pilots isotropically from reader.
• The received signal matrix at reader for tag’s $n$th symbol period can be written as:
\[ Y(n) = \left( h_U b(n) \ h_D^T + U \right) S + W = H_b(n) S + W \]

• Using pseudo-inverse of pilot matrix, signal available for detection at reader in vectorized form:
\[ y_v(n) = \text{vec} \left\{ Y(n) S^+ \right\} = b(n) h_v + u_v + \hat{w}_v = \begin{cases} a_0 h_v + w_v, & \text{bit ‘0’}, \\ (a_0 + a_1) h_v + w_v, & \text{bit ‘1’}, \end{cases} \]
where $h_v \triangleq \text{vec} \left\{ h_U \ h_D^T \right\}$ and $w_v \triangleq \text{vec} \left\{ U + \frac{W S^H}{E_p} \right\}$

• To derive the expression for BER in closed-form, we consider two approximations:
  a) Strong LoS component in BSC \(\rightarrow\) Point-wise product $h_U \odot h_D$ follows complex Gaussian with i.i.d entries
  b) All entries of $h_v$ are i.i.d. complex Gaussian and it can be approximated as:
\[ h_v \sim \mathcal{CN} \left( \mu_{h_v} \triangleq \text{vec} \left\{ \mathbb{E} \{ h_U \} \mathbb{E} \{ h_D^T \} \right\}, \frac{\beta^2 (1+2K)}{(1+K)^2} I_N \right), \forall K \gg 1 \]
Detection Hypothesis

- Using proposed approximations, the ML detection problem can be written as the hypothesis testing:

\[
\begin{align*}
    &\mathcal{H}_0 : \ y_v \sim \mathcal{CN}\left(\mu_0, \ \sigma_0^2 I_{N^2/4}\right), \quad \text{bit ‘0’}, \\
    &\mathcal{H}_1 : \ y_v \sim \mathcal{CN}\left(\mu_1, \ \sigma_1^2 I_{N^2/4}\right), \quad \text{bit ‘1’},
\end{align*}
\]

where \( \mu_0 \triangleq a_0 \mu_{hv} \), \( \mu_1 \triangleq (a_0 + a_1) \mu_{hv} \), \( \sigma_0^2 \triangleq |a_0|^2 \beta^2 + \sigma_f^2 \), \( \sigma_1^2 \triangleq |a_0 + a_1|^2 \beta^2 + \sigma_f^2 \), and \( \sigma_f^2 \triangleq \sigma_u^2 + \sigma_w^2 \).

- The probability density function (PDF) for \( y_v \) under the proposed hypothesis is defined as:

\[
p(y_v; \mathcal{H}_i) = \frac{e^{-\frac{1}{2}(y_v - \mu_i)^H \left[ \sigma_i^2 I_{N^2/4} \right]^{-1} (y_v - \mu_i)}}{(2\pi)^{N^2/8} \det^{1/2} \left\{ \sigma_i^2 I_{N^2/4} \right\}} = \left(2\pi\sigma_i^2\right)^{-N^2/8} e^{-\frac{\|y_v - \mu_i\|^2}{2\sigma_i^2}}
\]

- Using this PDF under the proposed hypothesis, the ML decision rule and hypotheses can be approximated to:

\[
\begin{align*}
    &\frac{p(y_v; \mathcal{H}_1)}{p(y_v; \mathcal{H}_0)} \overset{\mathcal{H}_1}{\gtrless} 1 \\
    &\begin{cases}
    \mathcal{H}_0 : & \frac{2\|y_v - \mu_0\|^2}{\sigma_0^2} \sim \chi^2_{N^2/2}, \quad \text{bit ‘0’}, \\
    \mathcal{H}_1 : & \frac{2\|y_v - \mu_1\|^2}{\sigma_1^2} \sim \chi^2_{N^2/2}, \quad \text{bit ‘1’}.
    \end{cases}
\end{align*}
\]
Approximation for BIT ERROR RATE (BER)

• Values for means of the underlying channel gains are difficult to obtain due to the practical constraints of the tags
• So, we set the value for these means to be zero for analytical tractability
• ML detection adopted at R, the approximated log-likelihood ratio to be set to zero and solved, is:

\[
\log \left( \frac{p(y_v; H_0)}{p(y_v; H_1)} \right) \approx \frac{N^2}{8} \log \left( \frac{\sigma_1^2}{\sigma_0^2} \right) + \frac{Z}{2\sigma_1^2} - \frac{Z}{2\sigma_0^2} = 0
\]

• Based on above conditionally defined key statistic, the ML decision rule can be approximated to:

\[
\|y_v\|^2 \overset{H_1}{\gtrsim} \|y_v\|^2 \overset{\text{th}}{\triangleq} N \frac{\sigma_1^2 \sigma_0^2}{4} \left( \frac{\sigma_1^2}{\sigma_1^2 - \sigma_0^2} \right) \log \left( \frac{\sigma_1^2}{\sigma_0^2} \right)
\]

• Finally, the desired BER expression can be approximated as below:

\[
p_{\text{be}} = \frac{1}{2} \frac{\Gamma \left( \frac{N^2}{4}, \frac{Z_{\text{th}}}{\sigma_1^2} \right) - \Gamma \left( \frac{N^2}{4}, \frac{Z_{\text{th}}}{\sigma_0^2} \right)}{2 \Gamma \left( \frac{N^2}{4} \right)}
\]

where \( \Gamma (s, x) = \int_x^\infty t^{s-1}e^{-t} \, dt \) is upper incomplete gamma function with \( \Gamma (s) = \Gamma (s, 0) \) being ordinary gamma function
OPTIMIZING BC DESIGN FOR MINIMIZING BER

• As BER is a function of squared-magnitude of backscattering coefficients (BC) -- $a_0$ and $a_1$

• We focus on optimizing the real values of $a_0$ and $a_1$ because T can then set its BC to underlying complex number

• Optimization problem for minimizing BER can be outlined as:

$$\mathcal{OP}_1 : \arg\min_{a_0, a_1} p_{be}, \quad \text{subject to}$$

(C1) $a_0, a_1 \geq 0$,  \hspace{1cm} (C’2) $a_0^2 + a_1^2 \leq a_{ub}$

where $a_{ub}$ is an upper bound on the reflection strength of BC at tag
Equivalent Univariate Transformation

• BER involves only two terms in the form of upper incomplete gamma functions which are dependent on BC variables \(a_0\) and \(a_1\)

• Upper gamma function is monotonically-decreasing in its second argument

• Minimizing BER is equivalent to maximizing the difference between these two upper incomplete gamma terms, which yields to below:

\[
\frac{Z_{th}}{\sigma_1^2} - \frac{Z_{th}}{\sigma_0^2} = \log\left(\frac{\sigma_1^2}{\sigma_0^2}\right) = \log\left(1 + \frac{(2a_1a_0 + a_1^2)}{\beta^2 a_0^2 + \sigma_1^2} \right)
\]

• Utilizing the monotonicity of the logarithmic function along with the fact that highest BC strength has to be exploited for minimizing BER, we can rewrite an equivalent single-variable optimization:

\[
\mathcal{O}P_2 : \argmax_{a_0} \frac{\beta^2 \left(2a_0 + \sqrt{a_{ub} - a_0^2}\right) \sqrt{a_{ub} - a_0^2}}{\beta^2 a_0^2 + \sigma_a^2 + \frac{\sigma_{ub}^2}{E_p}}
\]

subject to \((C3)\): \(0 \leq a_0 \leq a_{ub}\).
Globally-Optimal BC Design

• Objective is **non-concave** in the variable \( \rightarrow \) Simplified optimization problem is non-convex

• Taking **partial derivative** of objective with respect to the variable \( \alpha_0 \) and setting it to zero:

\[
\sigma_I^2 (a_{ub} - a_0^2) - \left( a_0 \sqrt{a_{ub} - a_0^2 + a_0^2} \right) \left( \beta^2 a_{ub} + \sigma_I^2 \right) = 0
\]

• Above is a **Quartic equation** having two negative (or infeasible) real roots and two positive (or feasible) roots
• One of them leads to maxima and other to its minima

• **Globally-optimal solution** over the feasible region is given by:

\[
a_0^* = \sqrt{\frac{a_{ub} (\beta^4 a_{ub}^2 + \beta^2 a_{ub} (4\sigma_I^2 - \sqrt{\omega}) + \sigma_I^2 (5\sigma_I^2 - \sqrt{\omega}))}{2 (\beta^4 a_{ub}^2 + \omega)}}
\]

with \( a_1^* \approx \sqrt{a_{ub} - (a_0^*)^2} \)
Validation of Analysis

- A very close match between the analytical and simulated results of both PDF and cumulative distribution function (CDF)
- It signifies the goodness of the proposed analytical approximation for distribution of $\|h_U \odot h_D\|^2$ for high Rice factor $K = 100$
- The RMSE value between the simulated and analytical results for BER over the considered range of SNR improves from 0.0336 to 0.0017 for $K = 0$ to $K = 15$
- Likewise, R-square statistics also respectively improves from 0.9924 to 0.9999
- This verifies the goodness of the proposed analytical approximation for BER
**BER Performance Comparison**

- **Average gap** between the simulation and analytical approximation results for BER over 200 kbits is $< 0.14$dB
- Smart selection of BC to $|\alpha_0| = 10^{-1}$, a ten-fold increase in $N$ can lead to **36dB improvement** in BER for SNR = 20dB
- Low BC value during off mode (or bit ‘0’) transmission may **not necessarily** lead to a lower BER
- Optimally-set BC using proposed design can yield **33dB improvement in BER** over arbitrarily selected ones
- Optimal value of BC ratio $\frac{|\alpha_0|}{|\alpha_1|}$ gets **reduced** for higher SNR and is **independent** of the underlying array-size $N$ at reader
Concluding Remarks

• A novel ML-based backscattering detection protocol for multiantenna reader-assisted monostatic BSC

• A three-phase transmission protocol and backscattering signal model that considers practical BSC constraints like UAR, strong LoS component, and tag’s resource-limitations

• Exploiting specific BSC features to come up with tight analytical approximation for BER

• Closed-form globally-optimal BC design at the tag that can provide significant improvement in BER

• Nontrivial insights from system engineering perspectives

• Observations can be used for designing sustainable low-power next-generation networks
Thank you for your attention!

For questions and feedback, please contact:

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