Optimizing Backscattering Coefficient Design for Minimizing BER at Monostatic MIMO Reader

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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

[1] C. Xu, L. Yang, and P. Zhang, "Practical backscatter communication systems for battery-free Internet of Things: A tutorial and survey of recent research," IEEE Signal Process. Mag., vol. 35, no. 5, pp. 16–27, Sept. 2018.
[2] D. Bharadia, K. R. Joshi, M. Kotaru, and S. Katti, "Backfi: High throughputWiFi backscatter," in Proc. ACM SIGCOMM, London, UK, Oct. 2015, pp. 283–296.
[3] D. Mishra and E. G. Larsson, "Optimal channel estimation for reciprocity-based backscattering with a full-duplex MIMO reader," IEEE Trans. Signal Process., vol. 67, no. 6, pp. 1662– 1677, Mar. 2019.

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]

[4] J. Qian, A. N. Parks, J. R. Smith, F. Gao, and S. Jin, "IoT communications with M-PSK modulated ambient backscatter: Algorithm, analysis, and implementation," IEEE Internet Things J., vol. 6, no. 1, pp. 844–855, Feb. 2019.
[5] A. Bekkali, S. Zou, A. Kadri, M. Crisp, and R. V. Penty, "Performance analysis of passive UHF RFID systems under cascaded fading channels and interference effects," IEEE Trans. Wireless Commun., vol. 14, no. 3, pp. 1421–1433, Mar. 2015.
[6] G. Zhu, S. Ko, and K. Huang, "Inference from randomized transmissions by many backscatter sensors," IEEE Trans. Wireless Commun., vol. 17, no. 5, pp. 3111–3127, May 2018.
[7] G. Yang, Q. Zhang, and Y. C. Liang, "Cooperative ambient backscatter communications for green internet-of-things," IEEE Internet Things J., vol. 5, no. 2, pp. 1116–1130, Apr. 2018.

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

[8] Y. Zhang, F. Gao, L. Fan, X. Lei, and G. K. Karagiannidis, “Backscatter communications over correlated Nakagami-m fading channels,” IEEE Trans. Commun., vol. 67, no. 2, pp. 1693–1704, Feb. 2019.
[9] D. Kim, H. Jo, H. Yoon, C. Mun, B. Jang, and J. Yook, “Reverse-link interrogation range of a UHF MIMO-RFID system in Nakagami-m fading channels,” IEEE Trans. Ind. Electron., vol. 57, no. 4, pp. 1468–1477, Apr. 2010.
[10] C. Boyer and S. Roy, “Space time coding for backscatter RFID,” IEEE Trans. Wireless Commun., vol. 12, no. 5, pp. 2272–2280, May 2013.
[11] D. Mishra and E. G. Larsson, “Multi-tag backscattering to MIMO reader: Channel estimation and throughput fairness,” IEEE Trans. Wireless Commun., vol. 18, no. 12, pp. 5584–5599, Dec. 2019.

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

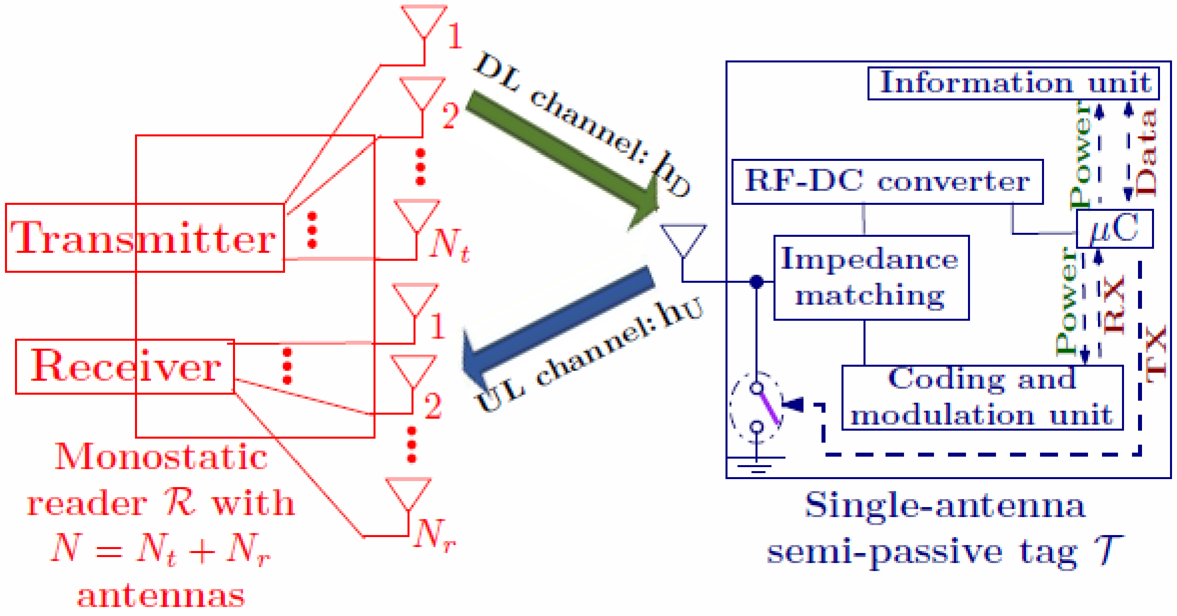
- The **key contribution** of this work is four-fold:
  a) Novel BSC transmission protocol for a MIMO reader to detect the backscattered signals from a single-antenna semi-passive tag
  b) Adopting ML detector at reader, tight analytical approximations for the optimal detection threshold and bit error 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

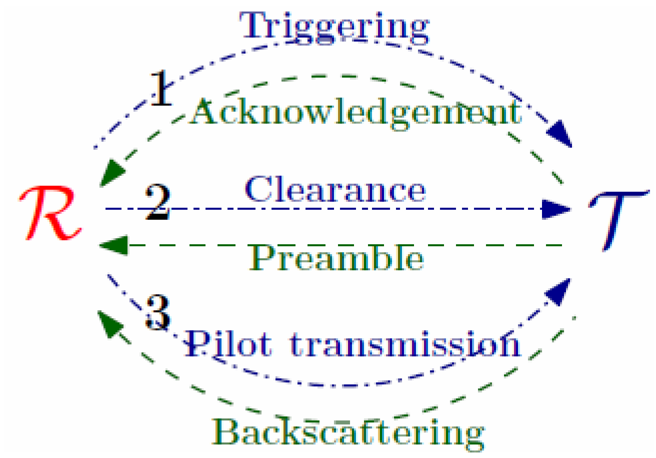
- The adopted **BSC model**:
  - *a)* N_t antennas at reader for transmission and N_r for receiving the backscattered signals
  - b) single-antenna tag
- Uniform linear array at the multiantenna reader
- Rician block fading model is adopted
- Binary modulated backscatter design involving amplitude shift 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 σ_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 nth symbol period can be written as:

$$\mathbf{Y}(n) = \left(\mathbf{h}_{\mathrm{U}}\, \mathrm{b}(n)\, \mathbf{h}_{\mathrm{D}}^{\mathrm{T}} + \mathbf{U}\right)\mathbf{S} + \mathbf{W} = \mathbf{H}_{\mathrm{b}}(n)\,\mathbf{S} + \mathbf{W}$$

- Using pseudo-inverse of pilot matrix, signal available for detection at reader in vectorized form:

$$\mathbf{y}_{\mathrm{v}}(n) = \mathrm{vec}\left\{\mathbf{Y}(n)\,\mathbf{S}^{\dagger}\right\} = \mathrm{b}(n)\,\mathbf{h}_{\mathrm{v}} + \mathbf{u}_{\mathrm{v}} + \widehat{\mathbf{w}}_{\mathrm{v}} = \begin{cases} a_0\,\mathbf{h}_{\mathrm{v}} + \mathbf{w}_{\mathrm{v}}, & \text{bit '0'}, \\ (a_0 + a_1)\,\mathbf{h}_{\mathrm{v}} + \mathbf{w}_{\mathrm{v}}, & \text{bit '1'}, \end{cases}$$

where $\mathbf{h}_{\mathrm{v}} \triangleq \mathrm{vec}\left\{\mathbf{h}_{\mathrm{U}}\,\mathbf{h}_{\mathrm{D}}^{\mathrm{T}}\right\}$ and $\mathbf{w}_{\mathrm{v}} \triangleq \mathrm{vec}\left\{\mathbf{U} + \frac{\mathbf{W}\,\mathbf{S}^{\mathrm{H}}}{\mathrm{E_p}}\right\}$

- To derive the expression for BER in **closed-form**, we consider two approximations:
  a) Strong LoS component in BSC → Point-wise product $\mathbf{h}_{\mathrm{U}} \odot \mathbf{h}_{\mathrm{D}}$ follows complex Gaussian with i.i.d enteries
  b) All entries of $\mathbf{h}_{\mathrm{v}}$ are i.i.d. complex Gaussain and it can be approximated as:

$$\mathbf{h}_{\mathrm{v}} \sim \mathcal{CN}\left(\boldsymbol{\mu}_{\mathbf{h}_{\mathrm{v}}} \triangleq \mathrm{vec}\left\{\mathbb{E}\left\{\mathbf{h}_{\mathrm{U}}\right\}\mathbb{E}\left\{\mathbf{h}_{\mathrm{D}}^{\mathrm{T}}\right\}\right\}, \frac{\beta^2(1+2K)}{(1+K)^2}\mathbf{I}_{\frac{N^2}{4}}\right), \forall K \gg 1$$

Detection Hypothesis

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

$$\begin{cases} \mathcal{H}_0 : \ \mathbf{y}_\mathrm{v} \sim \mathbb{CN}\left(\boldsymbol{\mu}_0, \ \sigma_0^2 \, \mathbf{I}_{\frac{N^2}{4}}\right), & \text{bit `0'}, \\ \mathcal{H}_1 : \ \mathbf{y}_\mathrm{v} \sim \mathbb{CN}\left(\boldsymbol{\mu}_1, \ \sigma_1^2 \, \mathbf{I}_{\frac{N^2}{4}}\right), & \text{bit `1'}, \end{cases}$$

where $\boldsymbol{\mu}_0 \triangleq a_0 \, \boldsymbol{\mu}_{\mathbf{h}_\mathrm{v}}$, $\boldsymbol{\mu}_1 \triangleq (a_0 + a_1) \, \boldsymbol{\mu}_{\mathbf{h}_\mathrm{v}}$, $\sigma_0^2 \triangleq |a_0|^2 \beta^2 + \sigma_I^2$, $\sigma_1^2 \triangleq |a_0 + a_1|^2 \beta^2 + \sigma_I^2$, and $\sigma_I^2 \triangleq \sigma_\mathrm{u}^2 + \frac{\sigma_\mathrm{w}^2}{\mathrm{E_p}}$

- The probability density function (PDF) for $\mathbf{y}_\mathrm{v}$ under proposed hypothesis is defined as:

$$p\left(\mathbf{y}_\mathrm{v}; \mathcal{H}_i\right) = \frac{\mathrm{e}^{-\frac{1}{2}(\mathbf{y}_\mathrm{v} - \boldsymbol{\mu}_i)^\mathrm{H} \left[\sigma_i^2 \, \mathbf{I}_{\frac{N^2}{4}}\right]^{-1} (\mathbf{y}_\mathrm{v} - \boldsymbol{\mu}_i)}}{(2\pi)^{\frac{N^2}{8}} \ \det^{\frac{1}{2}} \left\{\sigma_i^2 \, \mathbf{I}_{\frac{N^2}{4}}\right\}} = \left(2\pi\sigma_i^2\right)^{-\frac{N^2}{8}} \mathrm{e}^{-\frac{\|\mathbf{y}_\mathrm{v} - \boldsymbol{\mu}_i\|^2}{2\sigma_i^2}}$$

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

$$\frac{p\left(\mathbf{y}_\mathrm{v}; \mathcal{H}_1\right)}{p\left(\mathbf{y}_\mathrm{v}; \mathcal{H}_0\right)} \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} 1$$

$$\begin{cases} \mathcal{H}_0 : \ \frac{2\|\mathbf{y}_\mathrm{v} - \boldsymbol{\mu}_0\|^2}{\sigma_0^2} \sim \chi^2_{\frac{N^2}{2}}, & \text{bit `0'}, \\ \mathcal{H}_1 : \ \frac{2\|\mathbf{y}_\mathrm{v} - \boldsymbol{\mu}_1\|^2}{\sigma_1^2} \sim \chi^2_{\frac{N^2}{2}}, & \text{bit `1'}. \end{cases}$$

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:

$$\log\left(\frac{p\left(\mathbf{y}_{\mathrm{v}};\mathcal{H}_0\right)}{p\left(\mathbf{y}_{\mathrm{v}};\mathcal{H}_1\right)}\right)\approx\frac{N^2}{8}\log\left(\frac{\sigma_1^2}{\sigma_0^2}\right)+\frac{\mathcal{Z}}{2\sigma_1^2}-\frac{\mathcal{Z}}{2\sigma_0^2}=0$$

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

$$\|\mathbf{y}_{\mathrm{v}}\|^2 \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} \mathcal{Z}_{\mathrm{th}} \triangleq \frac{N^2}{4}\left(\frac{\sigma_1^2\,\sigma_0^2}{\sigma_1^2-\sigma_0^2}\right)\log\left(\frac{\sigma_1^2}{\sigma_0^2}\right)$$

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

$$p_{\mathrm{be}} \triangleq \frac{1}{2}-\frac{\Gamma\left(\frac{N^2}{4},\frac{\mathcal{Z}_{\mathrm{th}}}{\sigma_1^2}\right)-\Gamma\left(\frac{N^2}{4},\frac{\mathcal{Z}_{\mathrm{th}}}{\sigma_0^2}\right)}{2\,\Gamma\left(\frac{N^2}{4}\right)}$$

where $\Gamma(s,x)=\int_x^{\infty} t^{s-1}\mathrm{e}^{-t}\mathrm{d}t$ 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:

$$\mathcal{OP}_1: \underset{a_0, a_1}{\operatorname{argmin}} \quad p_{\mathrm{be}}, \qquad \text{subject to}$$
$$(\mathrm{C1}): a_0, a_1 \geq 0, \quad (\mathrm{C2}): a_0^2 + a_1^2 \leq a_{\mathrm{ub}}$$

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:

$$\frac{\mathcal{Z}_{\mathrm{th}}}{\sigma_1^2} - \frac{\mathcal{Z}_{\mathrm{th}}}{\sigma_0^2} = \log\left(\frac{\sigma_1^2}{\sigma_0^2}\right) = \log\left(1 + \frac{\left(2a_1a_0 + a_1^2\right)\beta^2}{\beta^2\, a_0^2 + \sigma_I^2}\right)$$

- 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**:

$$\mathcal{OP}_2: \quad \underset{a_0}{\operatorname{argmax}} \quad \frac{\beta^2\left(2a_0 + \sqrt{a_{\mathrm{ub}} - a_0^2}\right)\sqrt{a_{\mathrm{ub}} - a_0^2}}{\beta^2\, a_0^2 + \sigma_{\mathrm{u}}^2 + \frac{\sigma_{\mathrm{w}}^2}{\mathrm{E_p}}}$$

$$\text{subject to} \quad (\mathrm{C3}): \ 0 \le a_0 \le a_{\mathrm{ub}}.$$

Globally-Optimal BC Design

- Objective is non-concave in the variable → Simplified optimization problem is non-convex
- Taking partial derivative of objective with respect to the variable α_0 and setting it to zero:

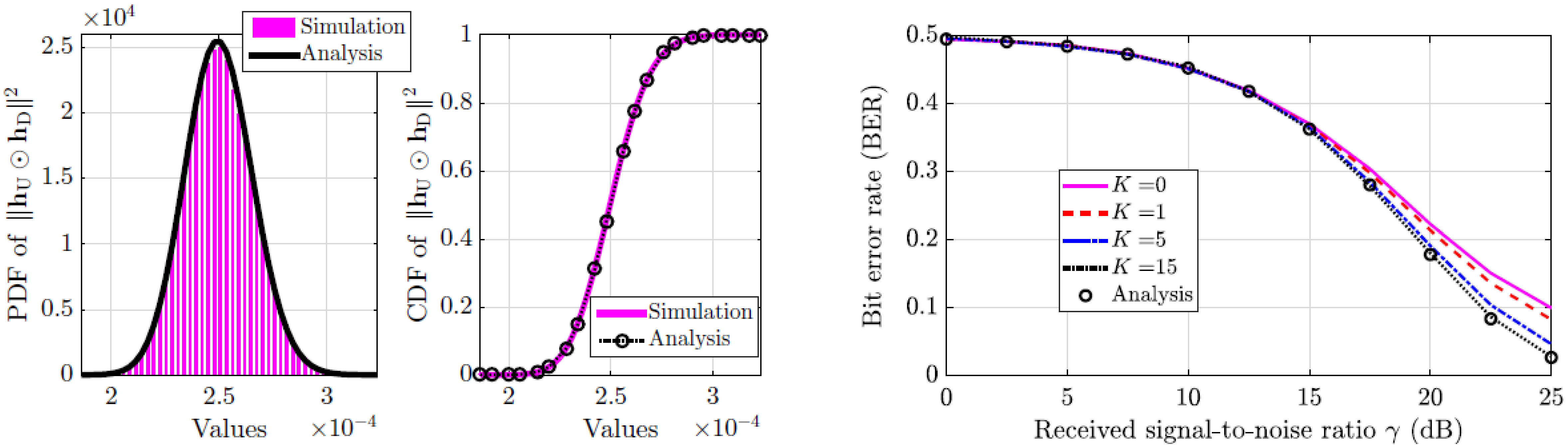
$$\sigma_I^2 \left(a_{\text{ub}} - a_0^2\right) - \left(a_0 \sqrt{a_{\text{ub}} - a_0^2} + a_0^2\right) \left(\beta^2 a_{\text{ub}} + \sigma_I^2\right) = 0$$

- 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:

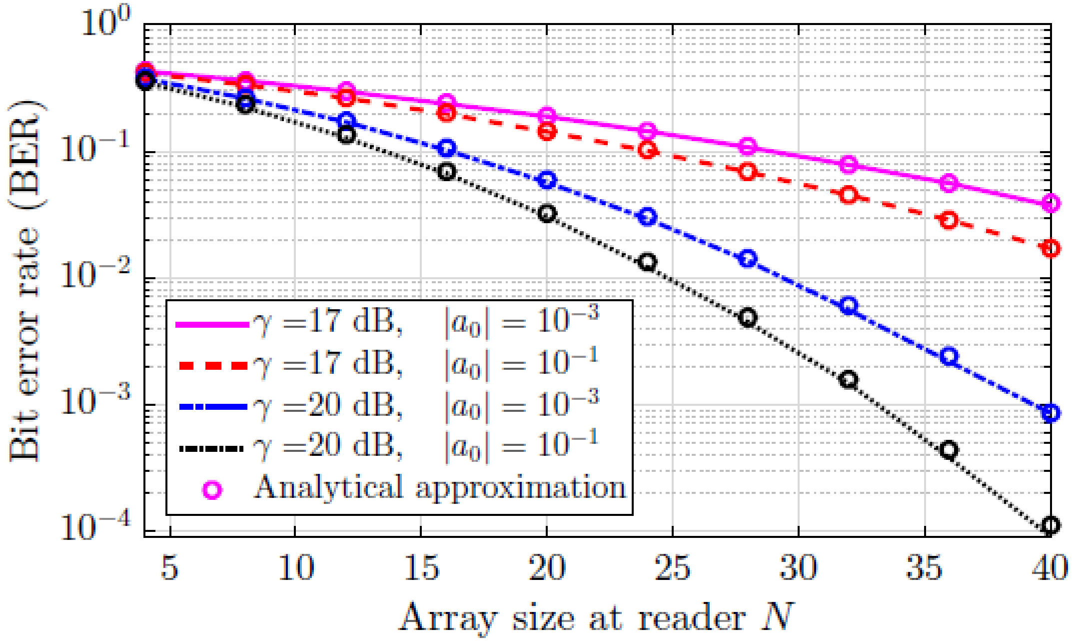
$$a_0^\star \triangleq \sqrt{\frac{a_{\text{ub}} \left(\beta^4 a_{\text{ub}}^2 + \beta^2 a_{\text{ub}} \left(4\sigma_I^2 - \sqrt{\varpi}\right) + \sigma_I^2 \left(5\sigma_I^2 - \sqrt{\varpi}\right)\right)}{2\left(\beta^4 a_{\text{ub}}^2 + \varpi\right)}} \quad \text{with } a_1^\star \triangleq \sqrt{a_{\text{ub}} - \left(a_0^\star\right)^2}$$

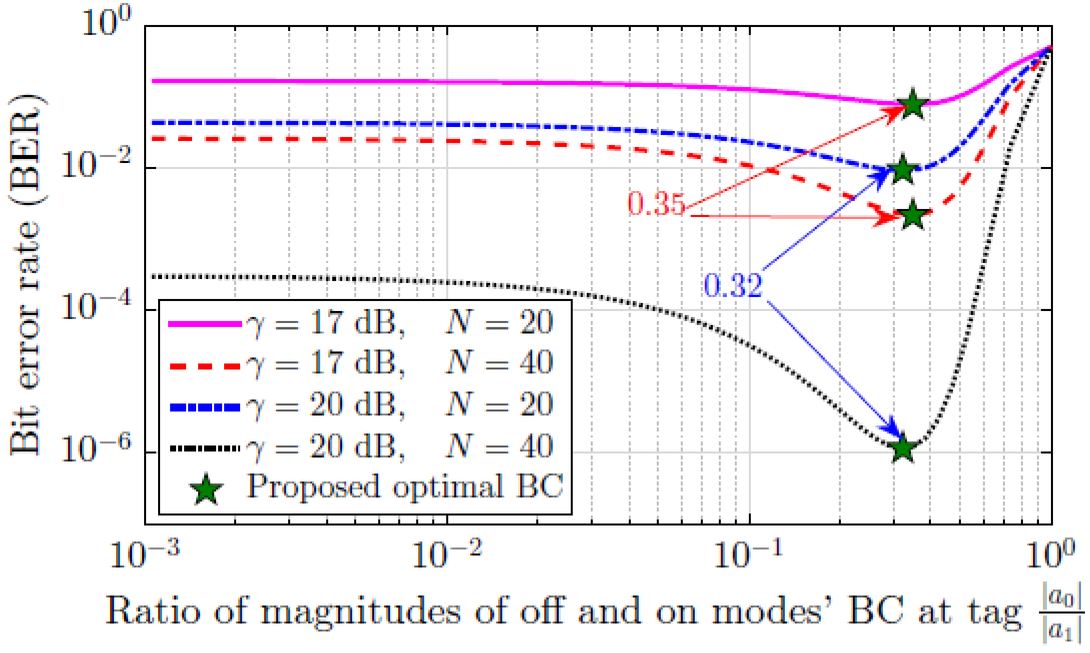
Validation of Analysis



- 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 $||\mathbf{h}_U \odot \mathbf{h}_D||^2$ 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 < 0.14dB
- Smart selection of BC to $|a_0| = 10^{-1}$, 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 $\frac{|a_0|}{|a_1|}$ 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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