PHYSICALLY CONSISTENT WIRELESS COMMUNICATIONS WITH STATISTICAL CHANNEL STATE INFORMATION

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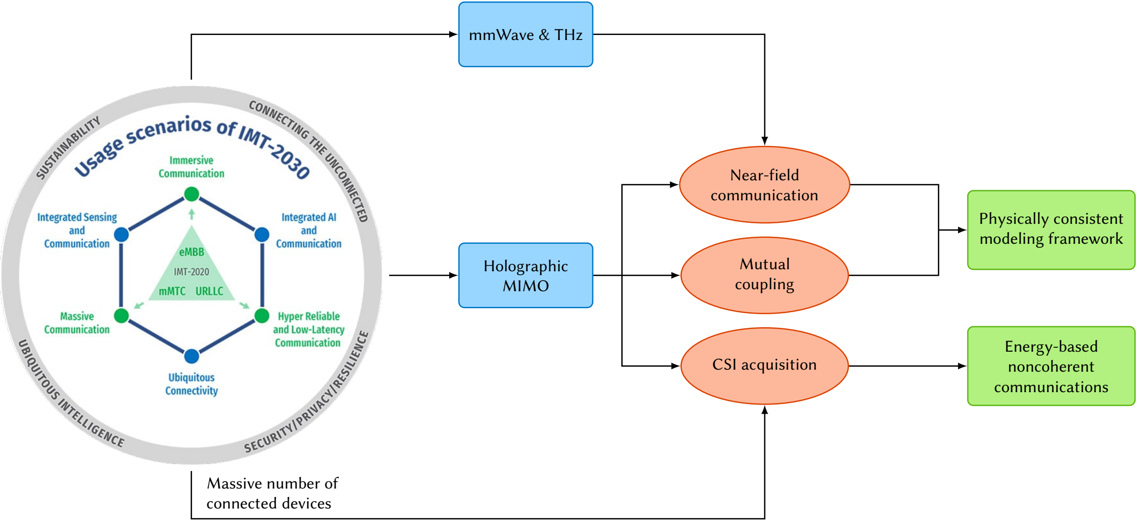
Motivation



ITU-R, “Framework and overall objectives of the future development of IMT for 2030 and beyond”

Outline

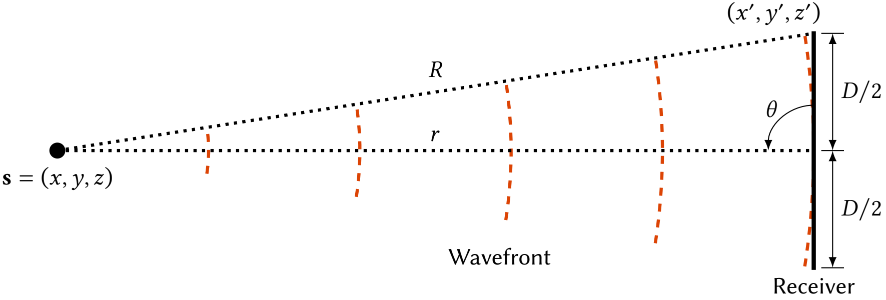
1. Physically consistent channel modeling
2. Energy-based noncoherent communications
3. Symbol detection with model-based receivers
4. Conclusions

Outline

1. Physically consistent channel modeling
    - Wavefront curvature
    - Mutual coupling
2. Energy-based noncoherent communications
3. Symbol detection with model-based receivers
4. Conclusions

Wavefront curvature

Traditional models relying on far-field and planar-wave assumptions become physically inconsistent as we move toward sub-THz frequencies and extremely large antenna arrays.



Array response

Near field: $\mathbf{a}(r, \theta, \phi)$ $\longleftrightarrow$ Spherical wavefront

$d_\mathrm{F} = 2D^2/\lambda$

Far field: $\bar{\mathbf{c}}(\theta, \phi)$ $\longleftrightarrow$ Planar wavefront

Spatial correlation

The multipath channel is given by the combination of L paths:

$$\mathbf{h}^{\mathrm{NLoS}} = \sum_{l=1}^{L} \alpha_l \cdot \underbrace{\mathbf{a}(r_l, \theta_l, \phi_l)}_{\text{Array response}}, \quad \alpha_l \in \mathbb{C}$$

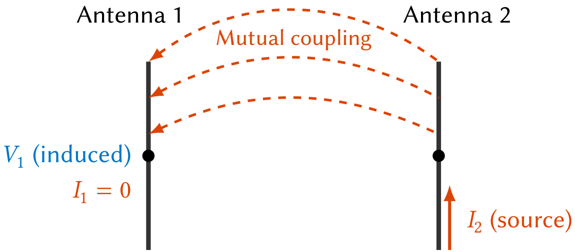
Under rich scattering, the channel follows a correlated Rayleigh fading model:

$$\mathbf{h} \sim \mathcal{CN}(\mathbf{0}_N, \mathbf{C}_{\mathbf{h}})$$

Covariance matrix

$$\mathbf{C}_{\mathbf{h}} = \mathrm{E}\left[\mathbf{h}\mathbf{h}^{\mathrm{H}}\right] = \sum_{l=1}^{L} \beta_l \mathbf{a}(r_l, \theta_l, \phi_l)\mathbf{a}(r_l, \theta_l, \phi_l)^{\mathrm{H}}$$

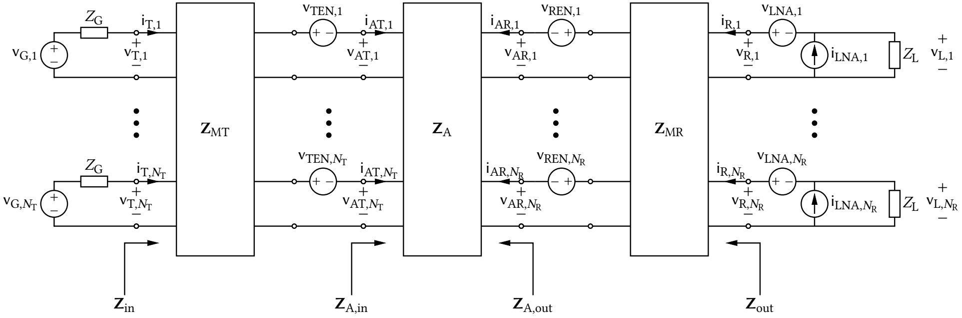
Mutual coupling is the electromagnetic interaction between nearby antenna elements, where the current from one source induces a voltage in another.



Mutual impedance

$$Z_{12} = \frac{V_1}{I_2}\Big|_{I_1=0}$$

Multiport communication theory



Matching networks

- Power/noise matching at the Tx/Rx.
- Difficult to implement in massive MIMO.
- No closed-form solution in the general case.

Information-theoretic and physical models

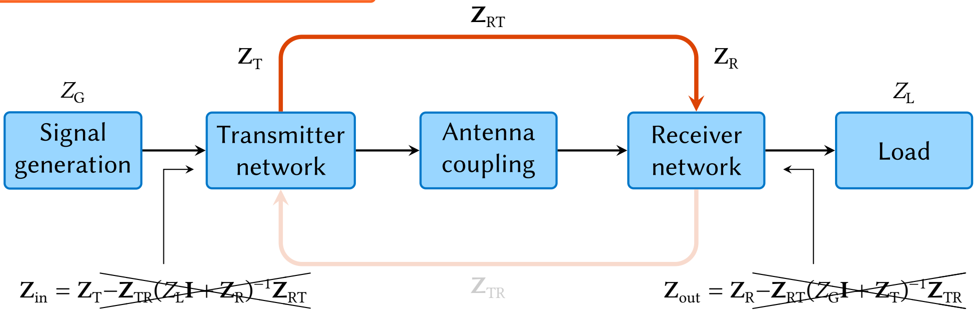
$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}, \quad \mathbf{z} \sim \mathcal{CN}(\mathbf{0}_{N_R}, \mathbf{C_z})$$

$$\mathbf{v}_L = \mathbf{D}\mathbf{v}_G + \mathbf{n}, \quad \mathbf{n} \sim \mathcal{CN}(\mathbf{0}_{N_R}, \mathbf{C_n})$$

Input-output relation

Unilateral approximation

$$\mathbf{Z}_{\text{TR}} \approx 0 \implies \mathbf{Z}_{\text{in}} \to \mathbf{Z}_{\text{T}},\ \mathbf{Z}_{\text{out}} \to \mathbf{Z}_{\text{R}}$$



Physical channel

$$\mathbf{D} = \underbrace{Z_{\text{L}}\left(Z_{\text{L}}\mathbf{I}_{N_{\text{R}}} + \mathbf{Z}_{\text{R}}\right)^{-1}}_{\mathbf{Q}} \mathbf{Z}_{\text{RT}}(Z_{\text{G}}\mathbf{I}_{N_{\text{T}}} + \mathbf{Z}_{\text{T}})^{-1}$$

Information-theoretic and physical models

Transmit power is the average active power delivered to the transmitting antennas:

$$P_\mathrm{T} = \mathrm{E}\left[\Re\left(\mathbf{v}_\mathrm{T}^\mathrm{H}\mathbf{i}_\mathrm{T}\right)\right] = \frac{\mathrm{E}\left[\mathbf{v}_\mathrm{G}^\mathrm{H}\mathbf{B}\mathbf{v}_\mathrm{G}\right]}{R_\mathrm{G}}, \quad \mathbf{B} = f(\mathbf{Z}_\mathrm{T})$$

Transmit power and noise must be equal in both models:

$$P_\mathrm{T} = \frac{\mathrm{E}\left[\mathbf{v}_\mathrm{G}^\mathrm{H}\mathbf{B}\mathbf{v}_\mathrm{G}\right]}{R_\mathrm{G}} = \mathrm{E}\left[\mathbf{x}^\mathrm{H}\mathbf{x}\right]$$

Physical model

$$\mathbf{v}_\mathrm{L} = \mathbf{D}\mathbf{v}_\mathrm{G} + \mathbf{n}$$

Information-theoretic model

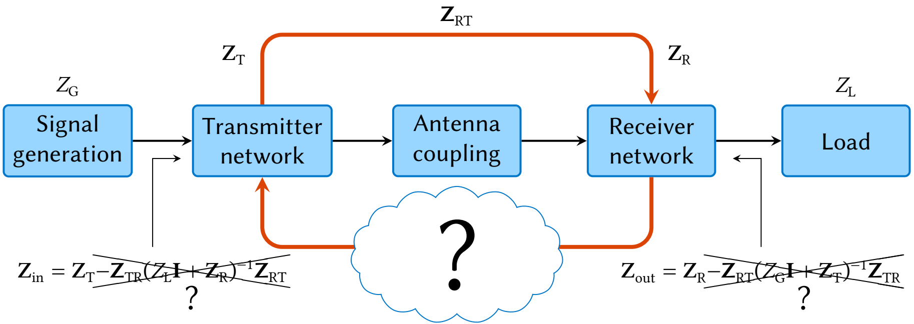
$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}$$

Physically consistent model

$$\begin{aligned} \mathbf{x} &= \mathbf{B}^{1/2}\mathbf{v}_\mathrm{G}/\sqrt{R_\mathrm{G}} \\ \mathbf{y} &= \mathbf{v}_\mathrm{L} \\ \mathbf{z} &= \mathbf{n} \end{aligned} \implies \mathbf{H} = \sqrt{R_\mathrm{G}}\underbrace{\left(\mathbf{Q}\mathbf{Z}_\mathrm{RT}(Z_\mathrm{G}\mathbf{I}_{N_\mathrm{T}} + \mathbf{Z}_\mathrm{T})^{-1}\right)}_{\mathbf{D}}\mathbf{B}^{-1/2}$$

Unilateral approximation: $\mathbf{x} \sim \mathbf{v}_\mathrm{G}$, $\mathbf{H} \sim \mathbf{Z}_\mathrm{RT} \rightarrow$ Correlated Rayleigh

Analysis of receiver to transmitter coupling



Unilateral condition

$$\left\| \mathbf{Z}_{\mathrm{TR}} \left(Z_{\mathrm{L}} \mathbf{I}_{N_{\mathrm{R}}} + \mathbf{Z}_{\mathrm{R}} \right)^{-1} \mathbf{Z}_{\mathrm{RT}} \right\|_{\mathrm{F}} \ll \|\mathbf{Z}_{\mathrm{T}}\|_{\mathrm{F}} \quad \overset{\text{MISO}}{\Longrightarrow} \quad \frac{\|\mathbf{z}_{\mathrm{TR}}\|_2^2}{|Z_{\mathrm{L}} + R_{\mathrm{r}}|} \ll \|\mathbf{Z}_{\mathrm{T}}\|_{\mathrm{F}}$$

$$\left\| \mathbf{Z}_{\mathrm{RT}} \left(Z_{\mathrm{G}} \mathbf{I}_{N_{\mathrm{T}}} + \mathbf{Z}_{\mathrm{T}} \right)^{-1} \mathbf{Z}_{\mathrm{TR}} \right\|_{\mathrm{F}} \ll \|\mathbf{Z}_{\mathrm{R}}\|_{\mathrm{F}} \quad \underset{\text{SIMO}}{\Longrightarrow} \quad \frac{\|\mathbf{z}_{\mathrm{RT}}\|_2^2}{|Z_{\mathrm{G}} + R_{\mathrm{r}}|} \ll \|\mathbf{Z}_{\mathrm{R}}\|_{\mathrm{F}}$$

Analysis of receiver to transmitter coupling

Hypotheses:

- LoS propagation.
- Single-user MISO/SIMO.
- ULA with aperture D and N elements.
- Inter-element spacing is d.
- Hertzian dipoles of length l.

Mutual coupling norms

Intra-array coupling admits the lower bound

$$\|\mathbf{Z}_{\mathrm{T}}\|_{\mathrm{F}} \geq \sqrt{N} \cdot \min_{m} \left\|[\mathbf{Z}_{\mathrm{T}}]_{m,*}\right\|_2 = \sqrt{N} \cdot \left\|[\mathbf{Z}_{\mathrm{T}}]_{1,*}\right\|_2$$

The squared norm of the inter-array coupling vector is

$$\|\mathbf{z}_{\mathrm{TR}}\|_2^2 = \frac{R_{\mathrm{r}}^2}{k^2} \sum_{n=0}^{N-1} \frac{1}{r_n^2} = \frac{R_{\mathrm{r}}^2}{k^2} \sum_{n=0}^{N-1} \frac{1}{r^2 + \left(\frac{nD}{N-1}\right)^2}$$

Fixed inter-element spacing

$$\|\mathbf{Z}_{\mathrm{T}}\|_{\mathrm{F}} \sim O(\sqrt{N})$$

$$\|\mathbf{z}_{\mathrm{TR}}\|_2^2 \sim O(1)$$

Fixed array size

$$\|\mathbf{Z}_{\mathrm{T}}\|_{\mathrm{F}} \sim O(N^{3.5})$$

$$\|\mathbf{z}_{\mathrm{TR}}\|_2^2 \sim O(N)$$

Unilateral approximation is fulfilled

Key takeaways

- **Wavefront curvature:** Near-field communications require spherical wavefront propagation models.
- **Mutual coupling:** Introduces structural channel correlation independent of spatial correlation.
- **Unilateral approximation:** Simplifies the analysis and yields correlated Rayleigh fading models. It remains valid throughout the radiative near field.

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1. Physically consistent channel modeling
2. Energy-based noncoherent communications
   - Asymptotic performance limits
   - Quadratic detection framework
   - Constellation design
   - Permutational index modulation
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Energy-based noncoherent communications

Acquiring instantaneous CSI in massive MIMO systems creates significant overhead, especially in high-mobility or sub-THz scenarios with short coherence times.

System model

Massive receiver array with N antennas:

$$\mathbf{y} = \mathbf{h}\mathrm{x} + \mathbf{z}, \quad \mathrm{x} \in \mathcal{X} = \{0, \ldots, \sqrt{\varepsilon_M}\}$$

↑ Unknown

- Fading is correlated Rayleigh.
- Noise is correlated Gaussian.
- Communication is one-shot.

By noise whitening and subsequent decorrelation of $\mathbf{y}$ we define

$$\mathbf{r}|x \sim \mathcal{CN}(\mathbf{0}_N, |x|^2\boldsymbol{\Gamma} + \mathbf{I}_N) \leftarrow \text{Diagonal}$$

ML detection

General ML detector:

$$\hat{x}_{\mathrm{ML}} = \arg\min_{x \in \mathcal{X}} \mathbf{r}^{\mathrm{H}}(|x|^2\boldsymbol{\Gamma} + \mathbf{I}_N)^{-1}\mathbf{r} + \ln\left||x|^2\boldsymbol{\Gamma} + \mathbf{I}_N\right|$$

Uncorrelated fading:

Energy estimation ↓

$$\hat{x}_{\mathrm{ML}} = \arg\min_{x \in \mathcal{X}} \frac{\mathbf{r}^{\mathrm{H}}\mathbf{r}}{|x|^2 + 1} + N \cdot \ln(|x|^2 + 1) \equiv \frac{\|\mathbf{r}\|^2}{N}$$

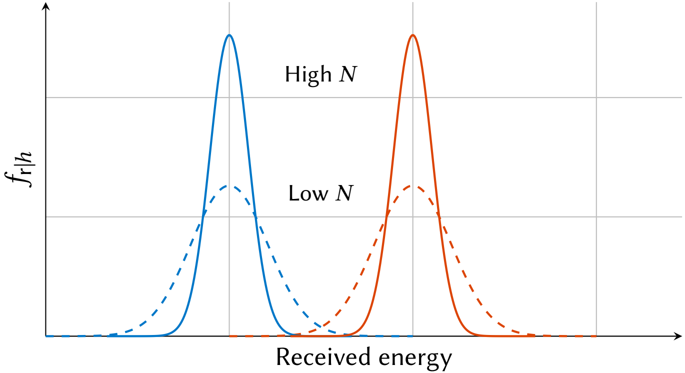
Asymptotic performance limits

Uniquely identifiable constellation (UIC)

$$|x_a|^2 \neq |x_b|^2 \iff x_a \neq x_b, \quad \forall x_a, x_b \in \mathcal{X}$$

Theorem 1 (channel hardening)

UICs are error-free as $N \to \infty$ and $\lim_{N\to\infty} \mathrm{tr}\left(\Gamma^2\right) = \infty$.



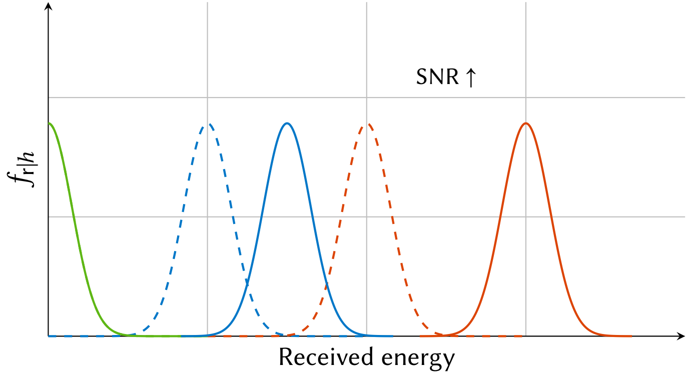
Asymptotic performance limits

Uniquely identifiable constellation (UIC)

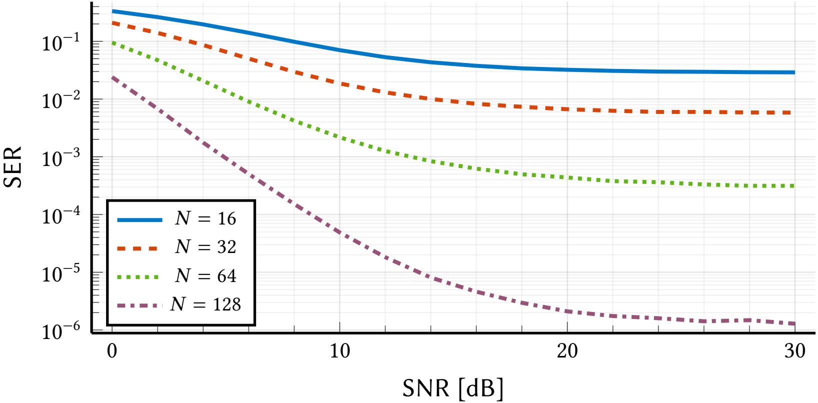
$$|x_a|^2 \neq |x_b|^2 \iff x_a \neq x_b, \quad \forall x_a, x_b \in \mathcal{X}$$

Theorem 2

UICs have an error floor at high SNR for $M > 2$.



Asymptotic performance limits



SER in terms of SNR under an exponentially correlated Rayleigh channel with $\rho = 0.8$ and a uniform unipolar 4-ASK constellation.

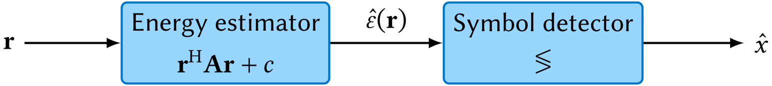
Energy statistic

Under uncorrelated Rayleigh fading and noise, the ML detector can be decomposed as:

1. Computation of a quadratic statistic in data: $\hat{\varepsilon}(\mathbf{r})$.
2. One-dimensional decision problem: $\hat{x}(\hat{\varepsilon})$.

Quadratic framework

$$\hat{\varepsilon}(\mathbf{r}) = \mathbf{r}^{\mathrm{H}}\mathbf{A}\mathbf{r} + c$$



Design coefficients $\mathbf{A}$ and c to maximize the mutual information between the transmitted symbol and the estimator output:

$$\mathrm{I}(\varepsilon;\hat{\varepsilon}) \geq \mathrm{h}(\varepsilon) - \mathrm{h}(\varepsilon - \hat{\varepsilon}) \geq \mathrm{h}(\varepsilon) - \frac{1}{2}(1 + \ln(2\pi \mathrm{var}(\xi))) = \mathrm{I}_{\mathrm{LOW}},$$

$$\hat{\varepsilon} = \arg\max_{\hat{\varepsilon}} \mathrm{I}_{\mathrm{LOW}} \equiv \arg\min_{\hat{\varepsilon}} \mathrm{var}(\xi), \quad \xi = \varepsilon - \hat{\varepsilon}$$

Quadratic estimation and detection

Best quadratic unbiased estimator (BQUE)

- Obtained by minimizing $\mathrm{var}(\hat{\varepsilon}|\varepsilon)$.
- Achieves the CRB.
- Genie-aided (unrealizable).

Quadratic minimum MSE (QMMSE)

- Obtained by minimizing $\mathrm{E}_\varepsilon[\mathrm{MSE}(\hat{\varepsilon}|\varepsilon)]$.
- Follows from the information-theoretic criterion.

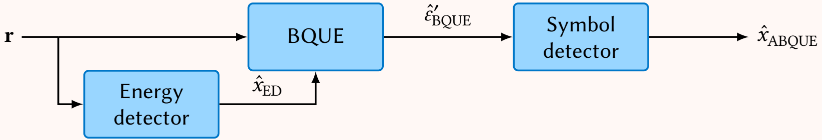
High SNR (HSNR)

- Derived as a high SNR approximation of the ML detector.

Energy detector (ED)

- Low-complexity technique that is well-known in the literature.

Assisted BQUE (ABQUE)



Detection regions

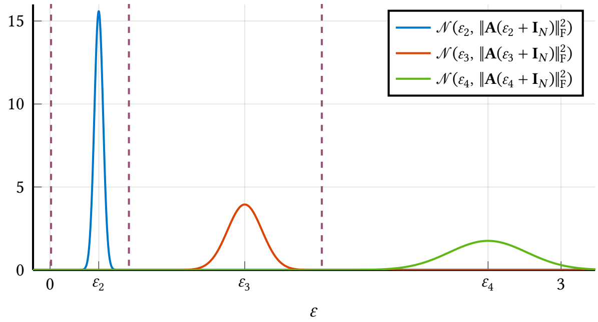
Central limit theorem

$\hat{\varepsilon}(\mathbf{r}|\varepsilon)$ follows a generalized chi-squared distribution, but as $N \to \infty$,

$$\hat{\varepsilon}(\mathbf{r}|\varepsilon) \xrightarrow{\mathrm{d}} \mathcal{N}\left(1-(1-\varepsilon)\mathrm{tr}(\mathbf{A}\boldsymbol{\Gamma}),\ \|\mathbf{A}(\varepsilon\boldsymbol{\Gamma}+\mathbf{I}_N)\|_{\mathrm{F}}^2\right)$$

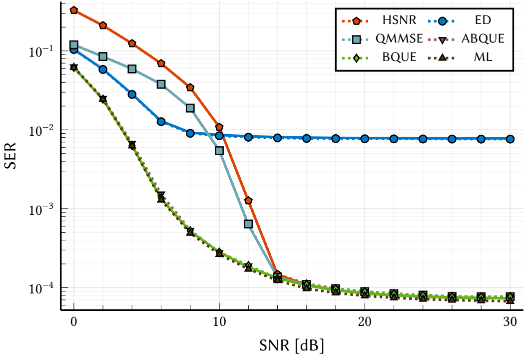
Proof: Lyapunov condition

Error probability can be written in closed-form in terms of Q-functions.

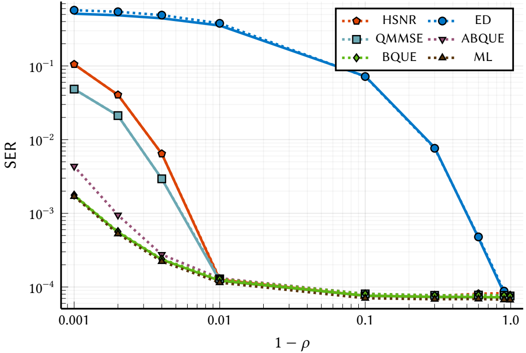


Detection regions of the BQUE for a 4-ASK with $N = 128$. Gaussian densities with different means but equal variance have a single intersection point.

Numerical results



SER of the presented detectors in terms of SNR for $N = 512$ and $\rho = 0.7$.



Floor level of the presented detectors in terms of ρ for $N = 512$.

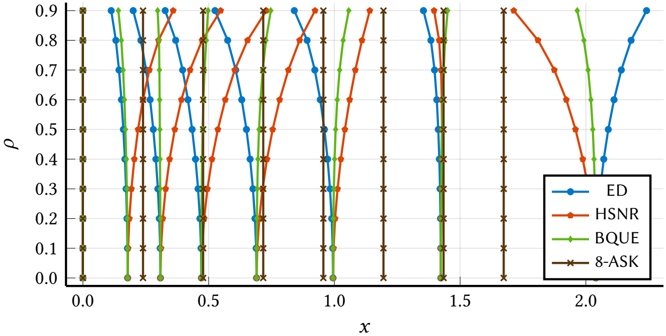
Error probability optimization

Deriving a closed-form expression for the error probability enables the design of constellations that minimize it, assuming statistical CSIT.

Optimization problem

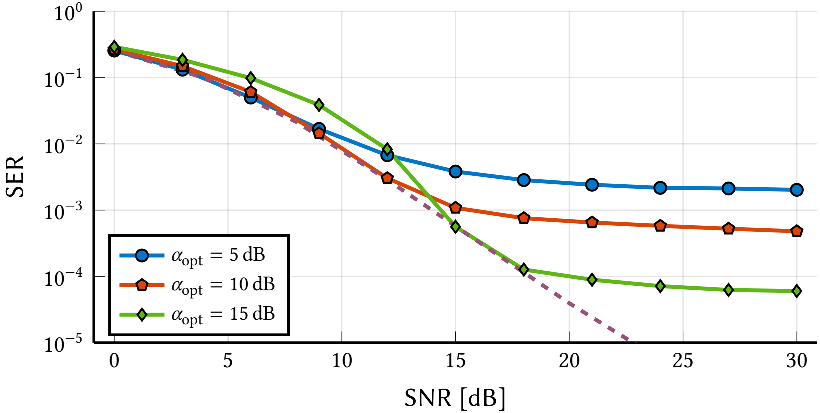
$$\begin{aligned}
\min_{\boldsymbol{\varepsilon},\boldsymbol{\tau}} \quad & P_{\epsilon}(\mathbf{A}, \boldsymbol{\varepsilon}, \boldsymbol{\tau}) \\
\text{s.t.} \quad & \boldsymbol{\varepsilon}, \boldsymbol{\tau} \geq \mathbf{0}, \\
& \varepsilon_1 = 0, \\
& \textstyle\sum_{i=1}^{M} \varepsilon_i = M, \\
& \varepsilon_i \leq \tau_i, \ i = 1, \dots, M-1, \\
& \tau_i \leq \varepsilon_{i+1}, \ i = 1, \dots, M-1,
\end{aligned}$$

where $\boldsymbol{\varepsilon} = (\varepsilon_1, \dots, \varepsilon_M)$ and $\boldsymbol{\tau} = (\tau_1, \dots, \tau_{M-1})$.



Comparison of optimized constellations at 15 dB and $N = 256$ for different exponential channel correlations.

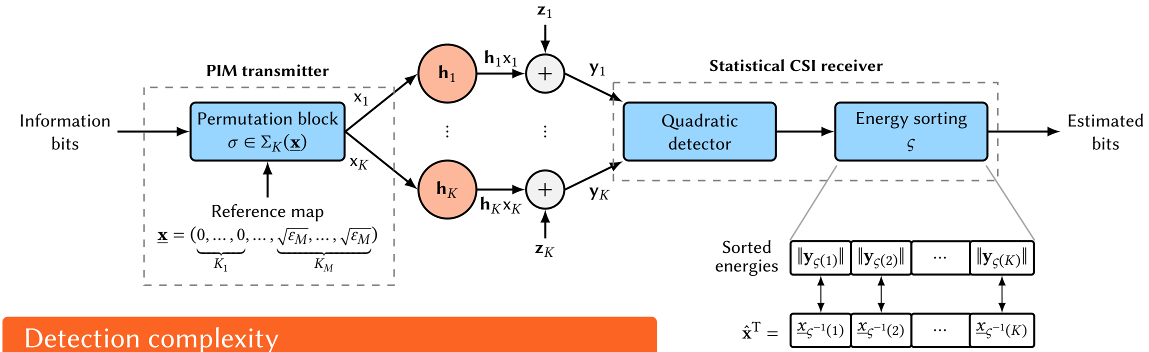
Numerical results



Error probability of BQUE when the constellation is optimized for a particular SNR.

Permutational index modulation

Transmitted energy can be reliably detected, so it becomes possible to convey information in the energy of each subcarrier of an OFDM system with K subcarriers.



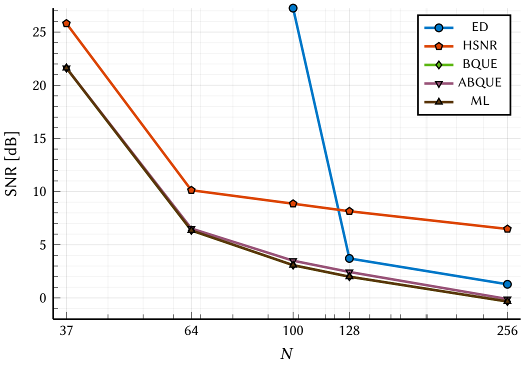
Detection complexity

Alphabet cardinality: $|\mathscr{A}| = K!/\prod_{m=1}^{M} K_m!$

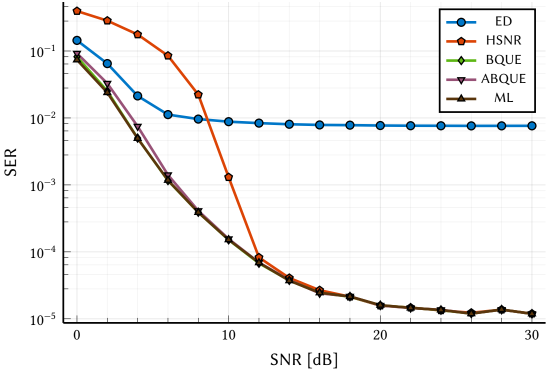
Maximum likelihood: $O(KN^2) + O(|\mathscr{A}|KN)$

Proposed scheme: $O(KN^2) + O(KN) + O(K \ln K)$

Numerical results



Required SNR to achieve SER = 10^{-3} in terms of N, for $\rho = 0.7$. A PIM with $K = 32$ and $M = 4$ is employed.



SER in terms of SNR for $N = 64$ and $\rho = 0.7$.

Key takeaways

- **Fundamental error floor:** In the absence of CSIT, constellations with more than two energy levels exhibit an error floor at high SNR.
- **Channel hardening:** Despite the SNR floor, the probability of error vanishes as the number of receiver antennas increases ($N \to \infty$).
- **Quadratic detection framework:** A novel class of quadratic detectors that leverage statistical CSI.
- **Optimized constellations:** By directly minimizing the analytical expression for the SER, it is possible to design constellations that eliminate the error floor.
- **Permutational index modulation (PIM):** Introduces coding gain in multicarrier systems by encoding information in the specific ordering of subcarrier energy levels.

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   - Mutual coupling and detection performance
   - Wavefront curvature in noncoherent detection
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Symbol detection with model-based receivers

Motivation

- **Model-based CSI:** High frequency systems estimate physical parameters $(\alpha_l, r_l, \theta_l, \phi_l)$ instead of full channel vectors.
- **The mismatch question:** Although precise models improve quality (especially at low SNR), oversimplification causes performance degradation.

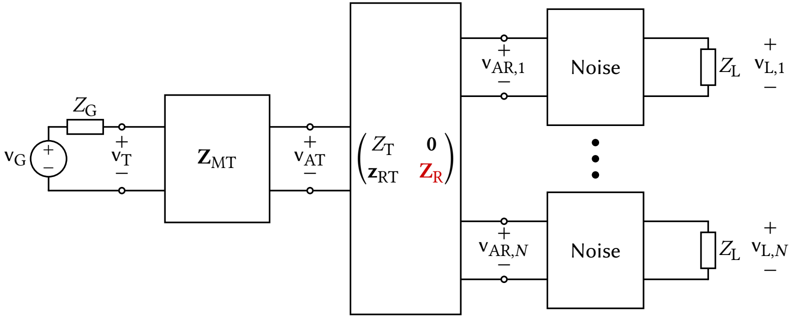
Scenario 1: Mutual coupling

- BS with densely deployed antennas.
- Affected by mutual coupling but operating completely unaware of it.
- Energy-based systems offer robustness to mutual coupling.

Scenario 2: Near-field curvature

- Exploits spherical wavefront curvature beyond the Fraunhofer limit.
- Avoids underestimating system capacity (unlike far-field approximations).
- Enables near-optimal detection with low complexity.

Mutual coupling and detection performance



Circuit model of a SIMO communication system with power matching at the transmitter.

Receiver array

N half-wavelength dipoles $\Longrightarrow$ Mutual coupling for $d \neq n\frac{\lambda}{2}$ $\Longrightarrow$ $\mathbf{Z}_R \not\propto \mathbf{I}_N$

Mismatched model $\Longrightarrow$ Assumes no coupling $\Longrightarrow$ $\mathbf{Z}_R \propto \mathbf{I}_N$

Receiver structure

Signal model

Received signal: $\mathbf{y} = \mathbf{h}x + \mathbf{z}$

From the multiport communication framework:

$$\mathbf{C_h} = R_\mathrm{r}^{-1}\mathbf{Q}\mathbf{C}_\mathrm{RT}\mathbf{Q}^\mathrm{H},$$
$$\mathbf{Q} = Z_\mathrm{L}(Z_\mathrm{L}\mathbf{I}_N + \mathbf{Z}_\mathrm{R})^{-1},$$
$$\mathbf{C_z} = \mathbf{Q}\mathbf{U}_\mathrm{n}\mathbf{Q}^\mathrm{H} \leftarrow \text{Depend on } \mathbf{Z}_\mathrm{R}$$

Coherent detector

MRC: $$\hat{x}_\mathrm{C} = \arg\min_{x\in\mathcal{X}} \left| \frac{\Re[\mathbf{h}^\mathrm{H}\mathbf{C}_\mathbf{z}^{-1}\mathbf{y}]}{\mathbf{h}^\mathrm{H}\mathbf{C}_\mathbf{z}^{-1}\mathbf{h}} - x \right|$$

Matched receiver

$$\mathbf{h} = -\mathrm{j}R_\mathrm{r}^{-1/2}\mathbf{Q}\mathbf{z}_\mathrm{RT}$$

Mismatched receiver

$$\hat{\mathbf{h}} = \sqrt{\gamma_1}\mathbf{z}_\mathrm{RT},\ \hat{\mathbf{C}}_\mathbf{z} = \gamma_2\mathbf{I}_N$$

Noncoherent detector

ML detector:

$$\hat{x}_\mathrm{NC} = \arg\min_{x\in\mathcal{X}} \mathbf{y}^\mathrm{H}\mathbf{C}_{\mathbf{y}|x}^{-1}\mathbf{y} + \ln|\mathbf{C}_{\mathbf{y}|x}|$$

Matched receiver

$$\mathbf{C}_{\mathbf{y}|x} = |x|^2\mathbf{C_h} + \mathbf{C_z}$$

Mismatched receiver

$$\hat{\mathbf{C}}_{\mathbf{y}|x} = \gamma_1|x|^2\mathbf{C}_\mathrm{RT}+\gamma_2\mathbf{I}_N$$

Robustness to mutual coupling at high SNR:

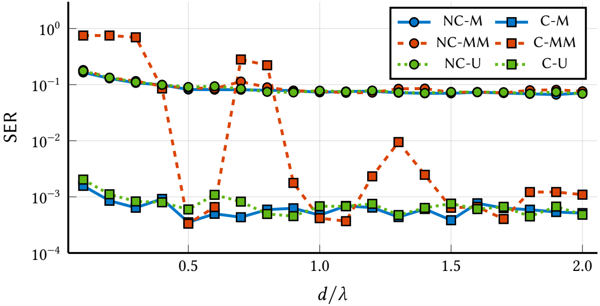
$$\mathbf{y}|x = \mathbf{h}x = \mathbf{Q}\underbrace{\alpha x\mathbf{z}_\mathrm{RT}}_{\text{Uncoupled signal}} = \mathbf{Q}\mathbf{r}|x,$$

ML detection:

$$\mathbf{y}^\mathrm{H}\mathbf{C}_{\mathbf{y}|x}^{-1}\mathbf{y} = \frac{\mathbf{r}^\mathrm{H}\mathbf{Q}^\mathrm{H}\Big(\overbrace{\mathbf{Q}\mathbf{C}_\mathrm{RT}\mathbf{Q}^\mathrm{H}}^{\mathbf{C_h}}\Big)^{-1}\mathbf{Q}\mathbf{r}}{|x|^2\beta} = \mathbf{r}^\mathrm{H}\mathbf{C}_{\mathbf{r}|x}^{-1}\mathbf{r}$$

Numerical results

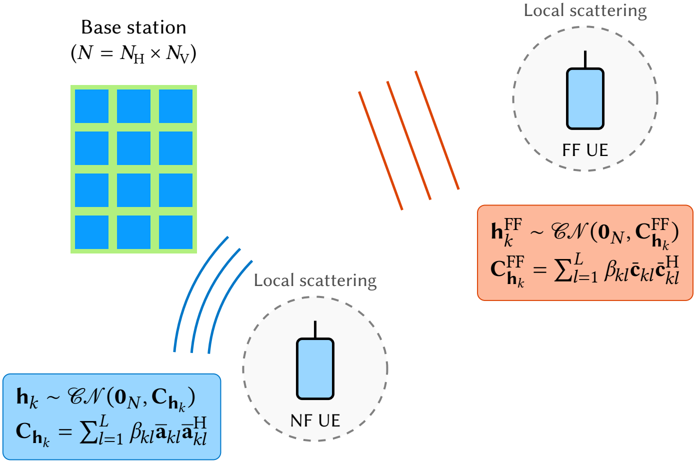
Parameter	Value	Parameter	Value
Carrier frequency	$f = 30\,\text{GHz}$	Variance of the current noise source	$\sigma_i^2 = 2k_B B_W T_A / R_N$
Bandwidth	$B_W = 20\,\text{MHz}$	Antenna impedance	$Z_A = 73 + \text{j}42.5\,\Omega$
Amplifier and load impedance	$Z_G = Z_L = 186 - \text{j}31.6\,\Omega$	Complex correlation coefficient	$\rho_N = 0.2730 + \text{j}0.1793$
Noise temperature of antennas	$T_A = 290\,\text{K}$	LNA resistance	$R_N = 5\,\Omega$



Error probability of the detectors as a function of element separation for $N = 128$ and $\text{SNR} = 5\,\text{dB}$.

Wavefront curvature in noncoherent detection

We consider the uplink of a noncoherent MIMO system with K users and a BS equipped with a $N = N_H N_V$ element UPA. The system operates under NLoS conditions with only statistical CSI.



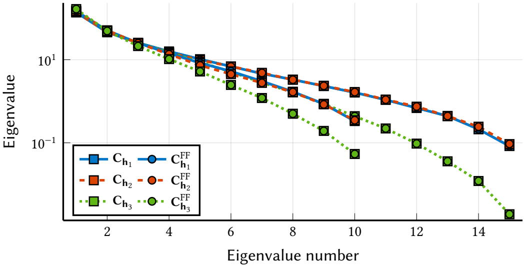
Channel statistics discussion

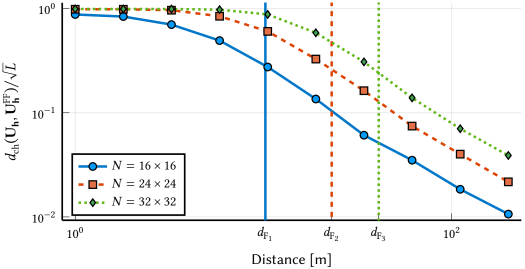
Spatial correlation spectrum

- Both far-field and near-field models exhibit the same correlation spectrum.
- If two users are in the same scattering cluster, their eigenvalues coincide.

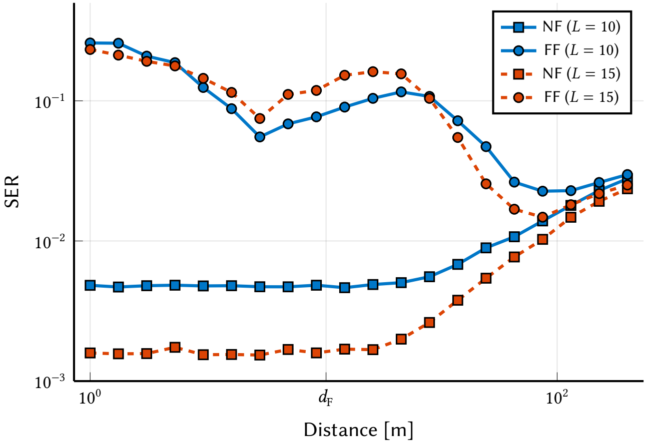
Distance between column spaces

- The chordal distance at the Fraunhofer limit is significant (30 % of its maximum value).
- When $N \to \infty$, $\mathrm{col}(\mathbf{C}_{\mathbf{h}}) \perp \mathrm{col}(\mathbf{C}_{\mathbf{h}}^{\mathrm{FF}})$, allowing large arrays to multiplex multiple users.





Numerical results



Error probability of a ML detector at different distances with SNR = 20 dB.

Single-user mismatched mode

- Far-field model severely underestimates performance up to $10d_F$.
- Higher SER at range due to lost spatial resolution between scatterers.

Outline

Conclusions

1. Shown that physically consistent models can be encapsulated into a **correlated Rayleigh fading** model.
2. Characterized the **asymptotic performance** of energy-based receivers.
3. Developed a framework of **quadratic detectors** for one-shot communications.
4. Implemented a **constellation optimization** algorithm to improve energy-based systems performance.
5. Proposed a **PIM scheme** for multicarrier energy-based systems to enhance performance.
6. Shown that noncoherent receivers are **robust to mutual coupling**, but accurate **near-field modeling** is crucial for detection.

Publications

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[5] **A. Martí**, M. Vilà-Insa, J. Riba, and M. Lamarca, "Constellation design for quadratic detection in noncoherent massive SIMO communications," in *2024 IEEE 25th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Lucca, Italy, 2024, pp. 566–570.

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[7] M. Vilà-Insa, **A. Martí**, J. Riba, and M. Lamarca, "Quadratic detection in noncoherent massive SIMO systems over correlated channels," *IEEE Transactions on Wireless Communications*, vol. 23, no. 10, pp. 14 259–14 272, 2024.

[8] **A. Martí**, F. de Cabrera, and J. Riba, "On the estimation of Tsallis entropy and a novel information measure based on its properties," *IEEE Signal Processing Letters*, vol. 30, pp. 818–822, 2023.

[9] **A. Martí**, J. Portell, J. Riba, and O. Mas, "Context-aware lossless and lossy compression of radio frequency signals," *Sensors*, vol. 23, no. 7, 2023.

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