LOW POWER SIGNAL PROCESSING STRATEGIES

DoD MURI Low Energy Electronics Design for Mobile Platforms

DOD-G-DAAH4-96-1-0377

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ARO-MURI RESEARCH MILESTONES

1. **Reduced wordlength strategies** for channel equalization and detection (Gupta)
    - **Fixed point LMS**: Transient and steady-state behavior (Hero&Gupta ISIT-98, SSAP-98, MILCOM-98, ICASSP-99, ICASSP-00, **TSP-01a**).

    - **Optimal compression for detection**
      (Gupta&Hero URSI-00, ISIT-01, SIAM-01, **TIT-01a**)
2. **Partial update strategies** for equalization and beamforming (Godavarti)
    - Stability analysis of S-LMS and P-LMS for cyclostationary signals
      (Godavarti&Hero ICASSP-99, ICASSP-01, **TSP-01b**).

- New stochastic P-LMS algorithm with better convergence (Godavarti&Hero SAM-00, ICASSP-01, **TSP-01c**).

3. **Space-time processing** and space-time coding (Godavarti)
   - **Cutoff rates and optimal power allocation** for Rayleigh fading (Hero&Marzetta SAM-00, ISIT-00, **TIT-01b**)

   - **Channel Capacity, diversity and DOF** for Rician Channels (Godavarti, Hero, Marzetta ISIT-01, Godavarti&Hero ISIT-02, ICASSP-02, URSI-02, **TIT-01c**, **TIT-01d**)
4. **Secure space time modulation** (Hero **TIT-01e**)

INDUSTRY/GOVT. INTERACTIONS

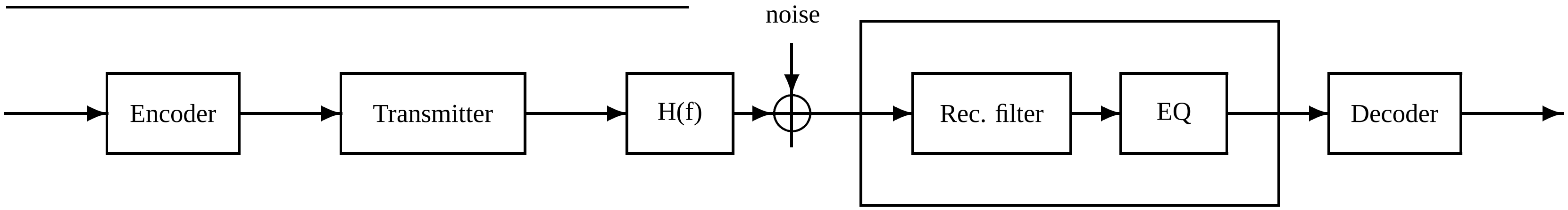
1. Invited seminars on low power MURI topics (Hero)

   Hughes Network Systems, Lucent Technologies, MIT Lincoln Laboratory, France Telecom

2. Industrial Internships
   - Bell Labs, Lucent Technologies (Murray Hill) - Hero (1999)
   - Bell Labs, Lucent Technologies (Murray Hill) - Godavarti (2000)
   - Rockwell Inc. (LA) - Gupta (2000)

3. Government Panels and Study Groups (Hero)
   DARPA (2000), SEDD-ARL (2002)

LOW POWER ADAPTATION



Objective: Reduce power consumption of channel equalizer with minimal loss in adaptation performance.

Other applications:

- System ID (channel identification)
- Adaptive beamforming
- Adaptive interference cancellation

Innovation on previous work: Power-optimal bit allocation. (Caraiscos&Liu 84, Alexander 87, Douglas&Meng 91, Bershad&Bermudez 96)

Fixed point LMS adaptation

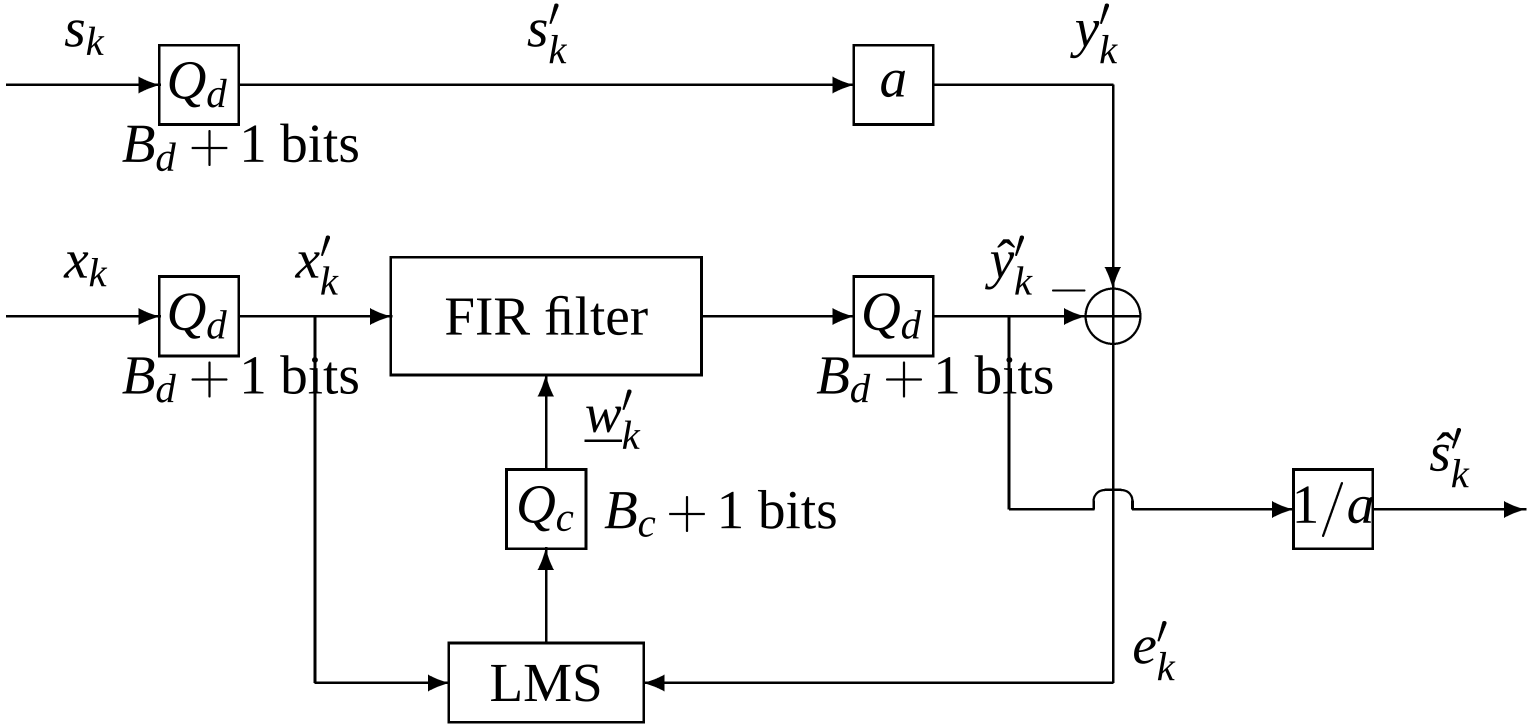
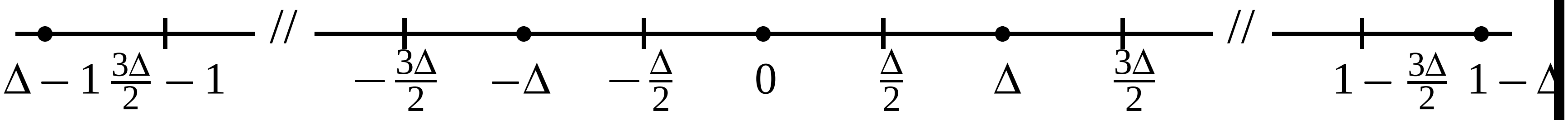


Figure 1. Finite precision LMS algorithm.



Fixed Point LMS Adaptation

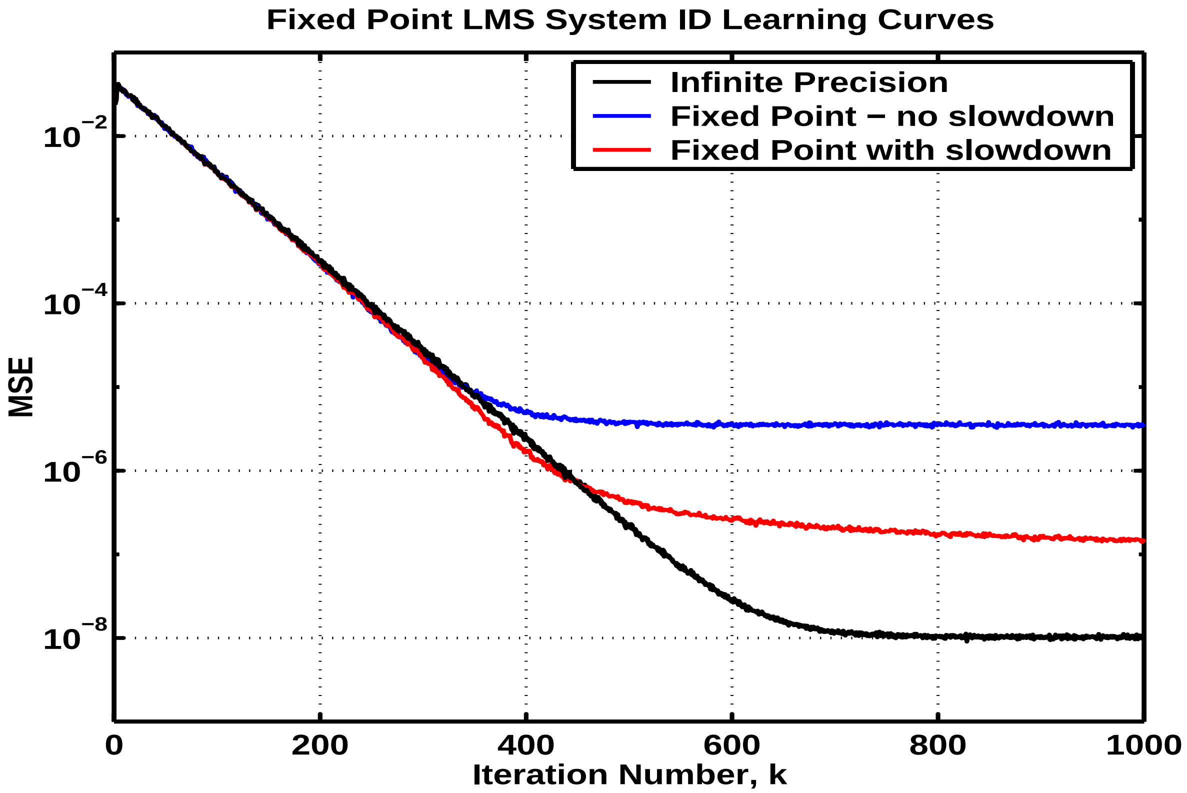


Figure 2. Fixed point LMS learning curves.

Note **“slowdown”** in red curve and **residual MSE** in blue curve.

Power Optimization of Finite Resolution MSE

Finite resolution LMS power consumption:

$$\begin{aligned} P_T &= 4p[(2B_d + B_c + 2)\eta_a + (3B_d + B_c)\eta_t] \\ \eta_a, \eta_t &= \text{power per add, table lookup} \end{aligned}$$

Bit allocation factor ρ:

$$\rho = \frac{B_d}{B_d + B_c}$$

Can **optimize** ρ with respect to steady-state MSE with **power constraint**, assuming no slowdown.

$$\rho^P = \min\{\rho_{slow}, \rho^{**}\}$$

ρ_{slow} = maximum ρ such that slowdown does not occur.
ρ^{**} = optimal ρ with respect to MSE.

Power Optimization: Example

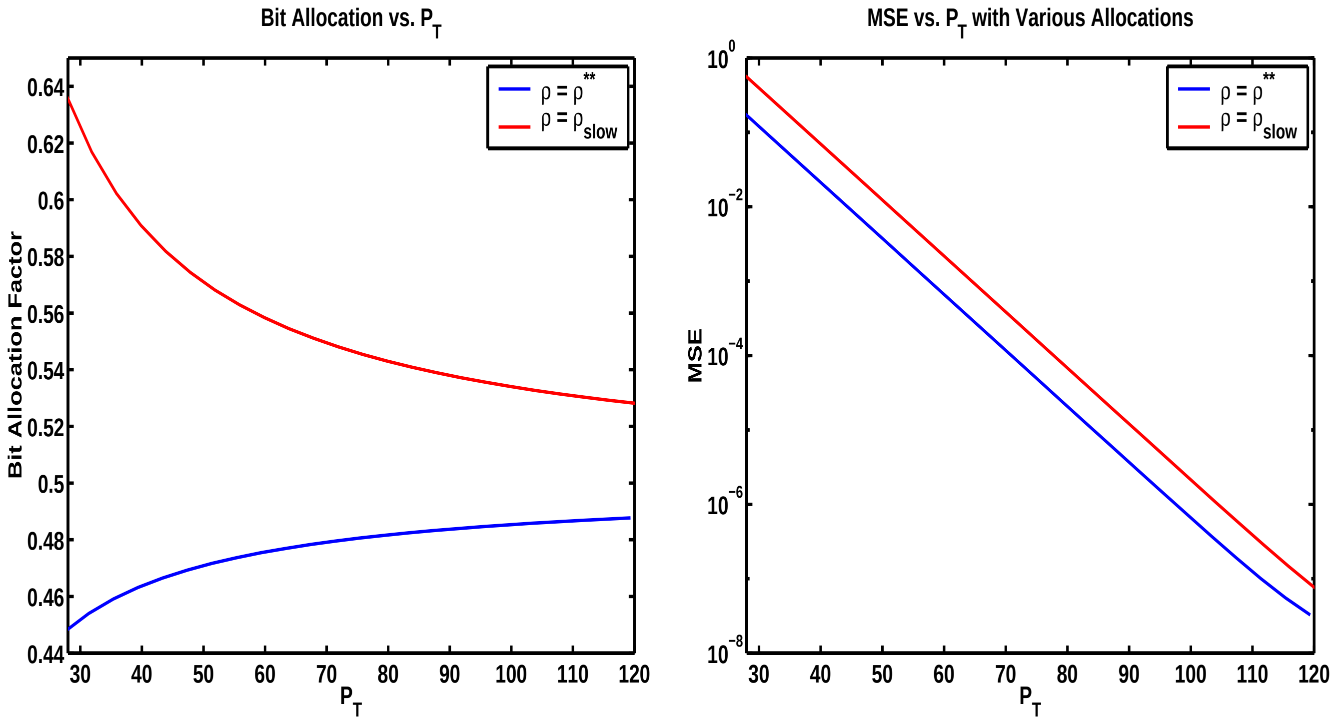


Figure 3. Optimal bit allocation and resultant MSE for LMS channel equalization example.

Partial Update LMS Algorithm

- Partial Update LMS Algorithm: Only a subset of LMS coefficients updated per iteration (Douglas, Godavarti, Messerschmitt)
- Advantages:
  - Computational and memory savings
  - Power savings
- Existing Partial Update LMS (PU-LMS) Algorithms
  - Periodic (**P-LMS**) and Sequential (**S-LMS**) Partial Update LMS
- Contributions
  - Tight convergence conditions on **P-LMS** and **S-LMS** (Godavarti&Hero ICASSP99, ICASSP01)
  - New Stochastic P-LMS Algorithm (**SPU-LMS**) with better convergence properties (Godavarti&Hero SAM00)

Sequential Partial Update LMS Algorithm

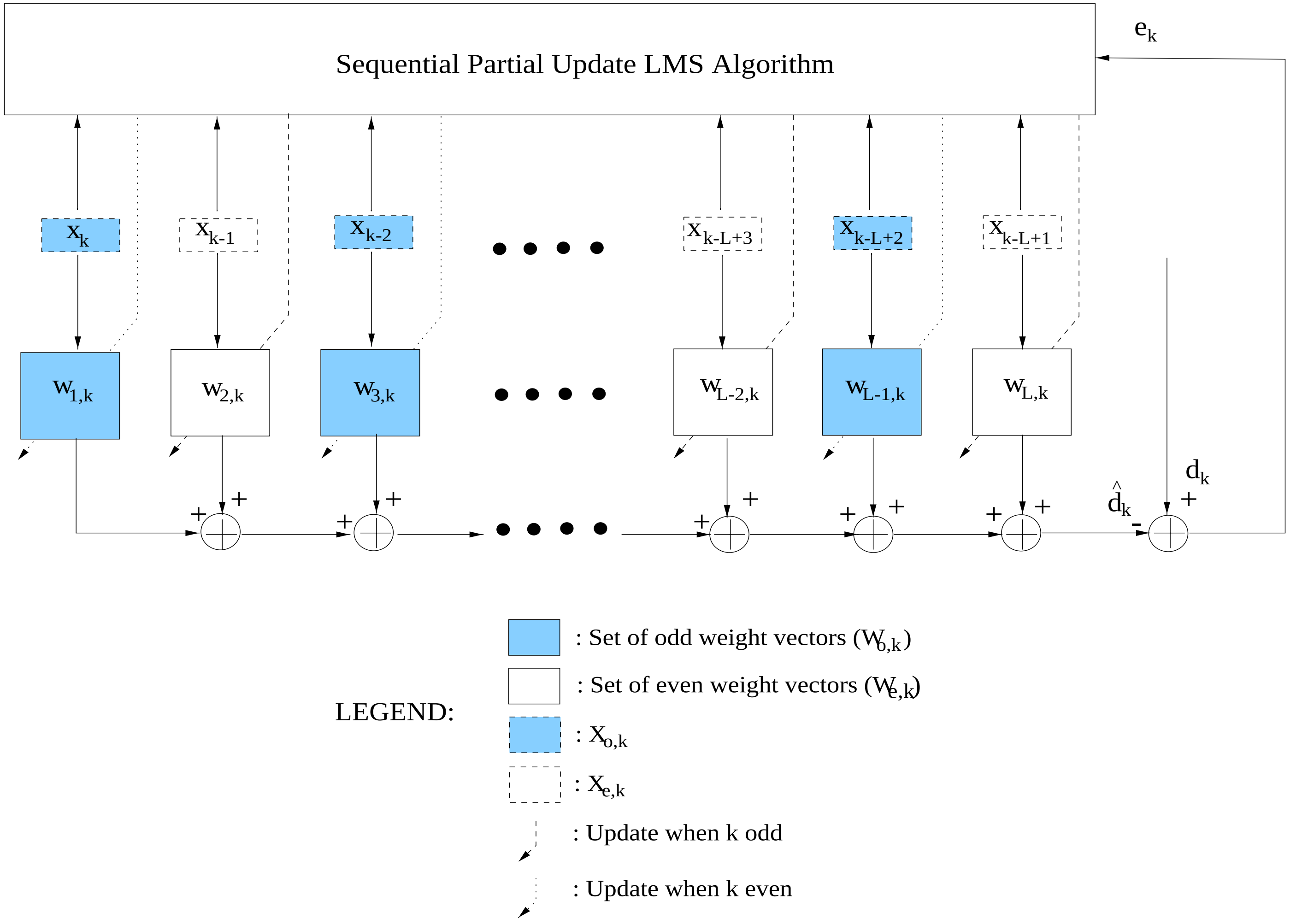
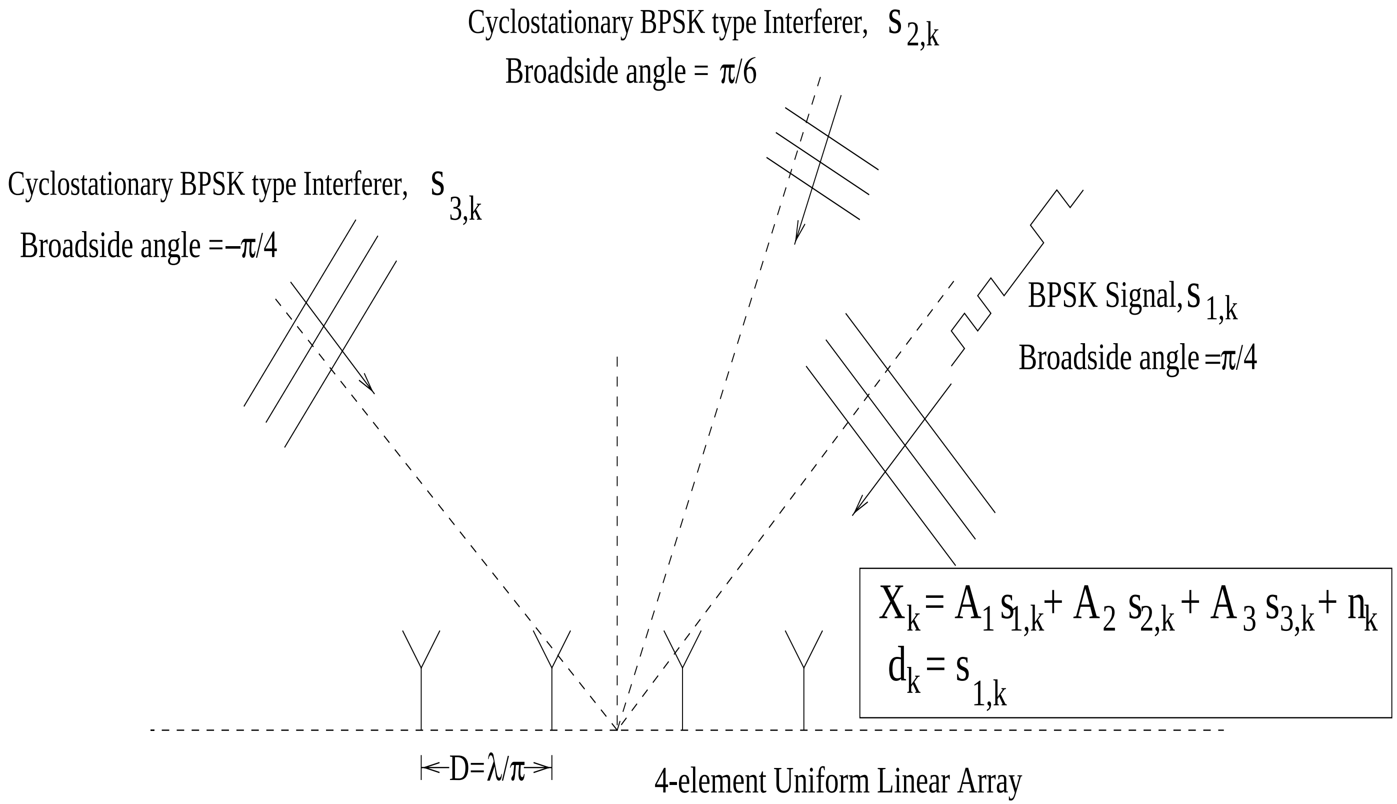


Figure 4. Block diagram of the sequential LMS algorithm.

Example: Non-Stationary Signal Scenario



$$X_k = A_1 s_{1,k} + A_2\, s_{2,k} + A_3\, s_{3,k} + n_k$$
$$d_k = s_{1,k}$$

Figure 5. Signal scenario for the example

- **SPU-LMS** randomly updates one coefficient per iteration
- **P-LMS** updates every fourth instant
- **S-LMS** updates one coefficient per iteration in the order $\{1, 2, 3, 4\}$.

Example cont'd

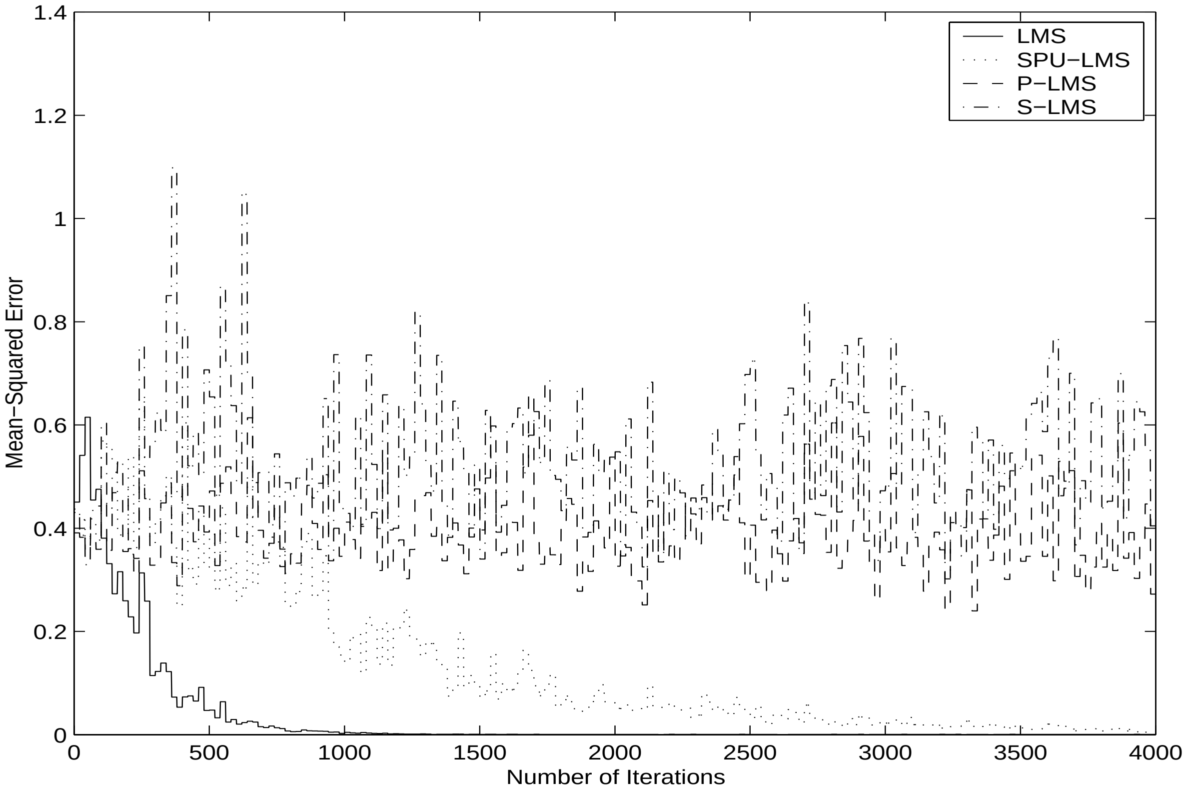


Figure 6. Envelopes of trajectories of all algorithms for Example 2. S-LMS and P-LMS failed to converge for all observed values of $\mu > 0$

Example cont'd

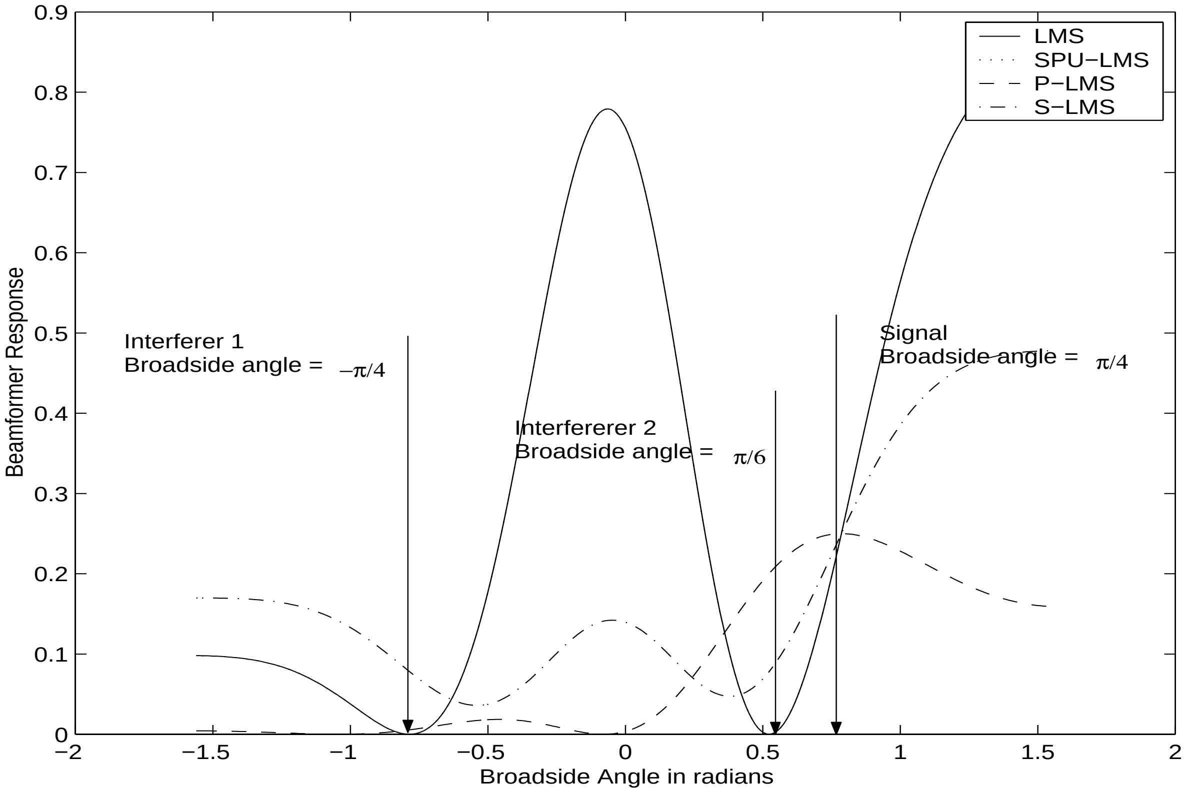
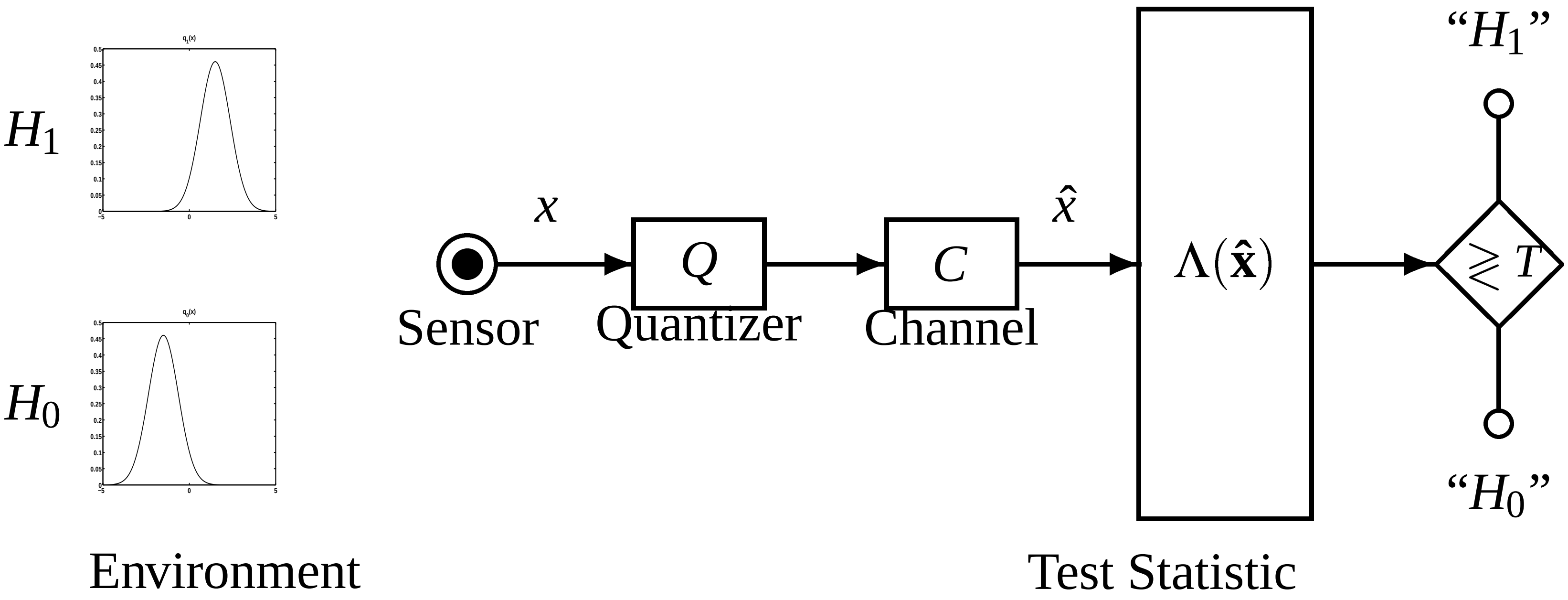


Figure 7. Best possible beampatterns generated by all algorithms. LMS and SPU-LMS have indentical beamformer response characteristics.

HYPOTHESIS TESTING FROM Q/VQ DATA

Objective: Observe $\hat{x} = Q(x)$ and decide between H_0 and H_1



H_1

H_0

x

$\hat{x}$

Q

C

$\Lambda(\hat{\mathbf{x}})$

$\gtrless T$

“H_1”

“H_0”

Sensor

Quantizer

Channel

Environment

Test Statistic

Objective: What is best way to compress images sequence to minimize loss in detection performance?

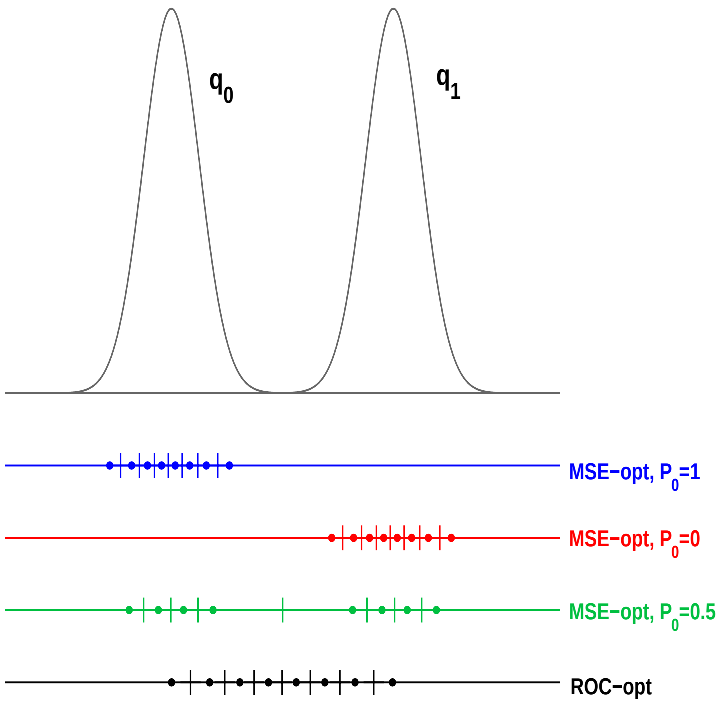
Other applications:

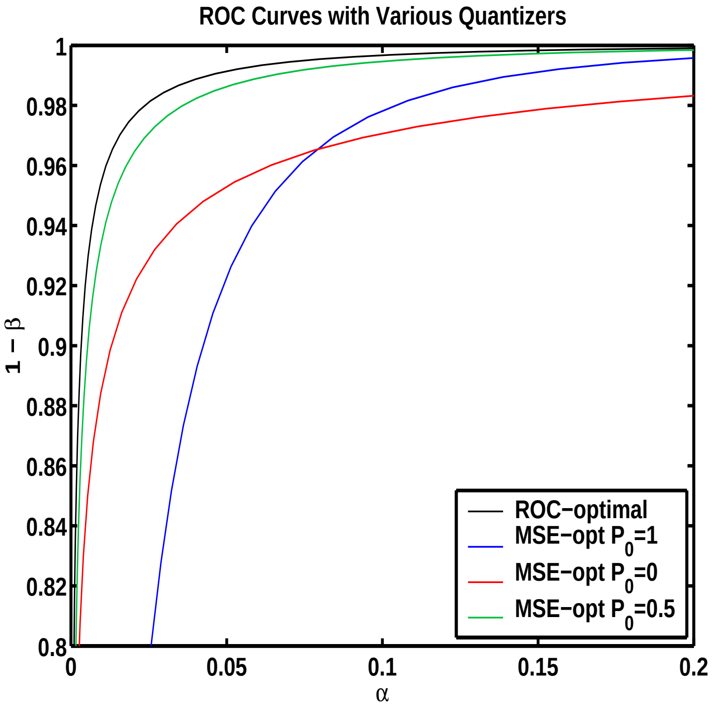
- Target recognition
- Classification
- Indexing databases
- Medical imaging

Innovation on previous work: High-rate, detection-optimal vector quantization.

- VQ: Oehler, Gray 96; Perlmutter et. al. 96.
- Scalar Quantization: Poor, Thomas 77, 83; Benitz, Bucklew 89; Picinbono, Duvaut 88.
- MSE-opt VQ: Gersho 79; Zador 82; Na, Neuhoff 95.

ROC Performance of Various Quantizers





2-D Anisotropic Gaussian Example

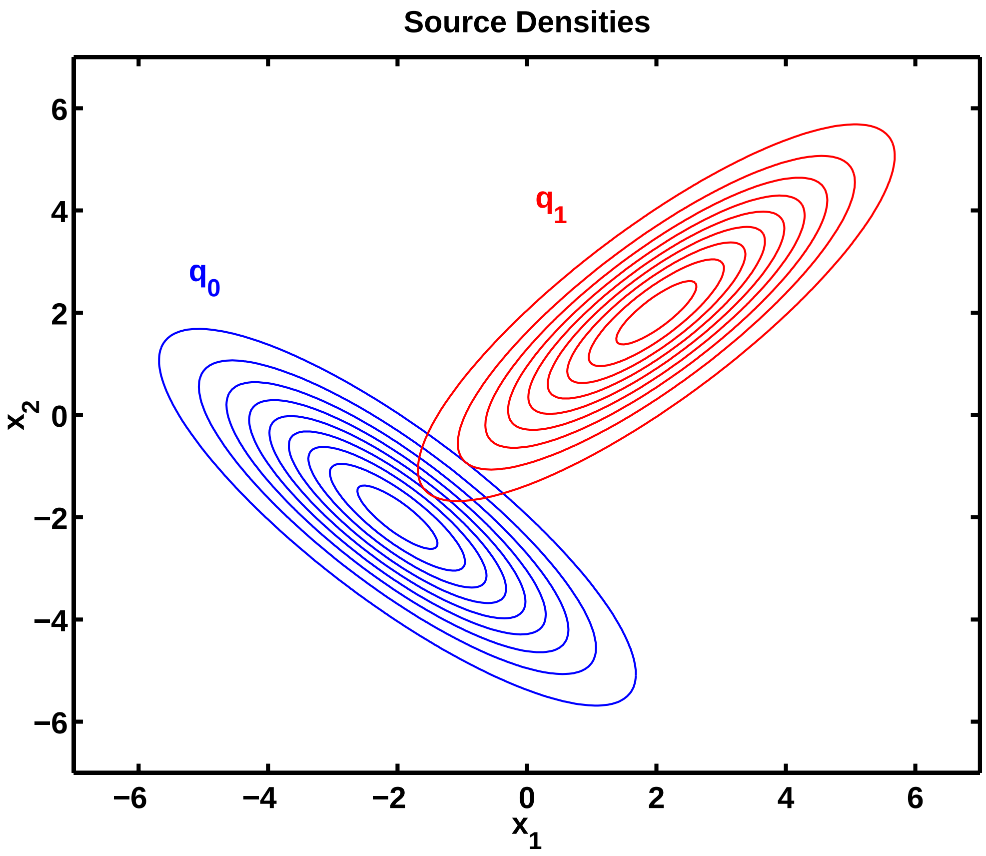


Figure 8. *Source densities for 2-D anisotropic Gaussian example.*

2-D Anisotropic Gaussian Example

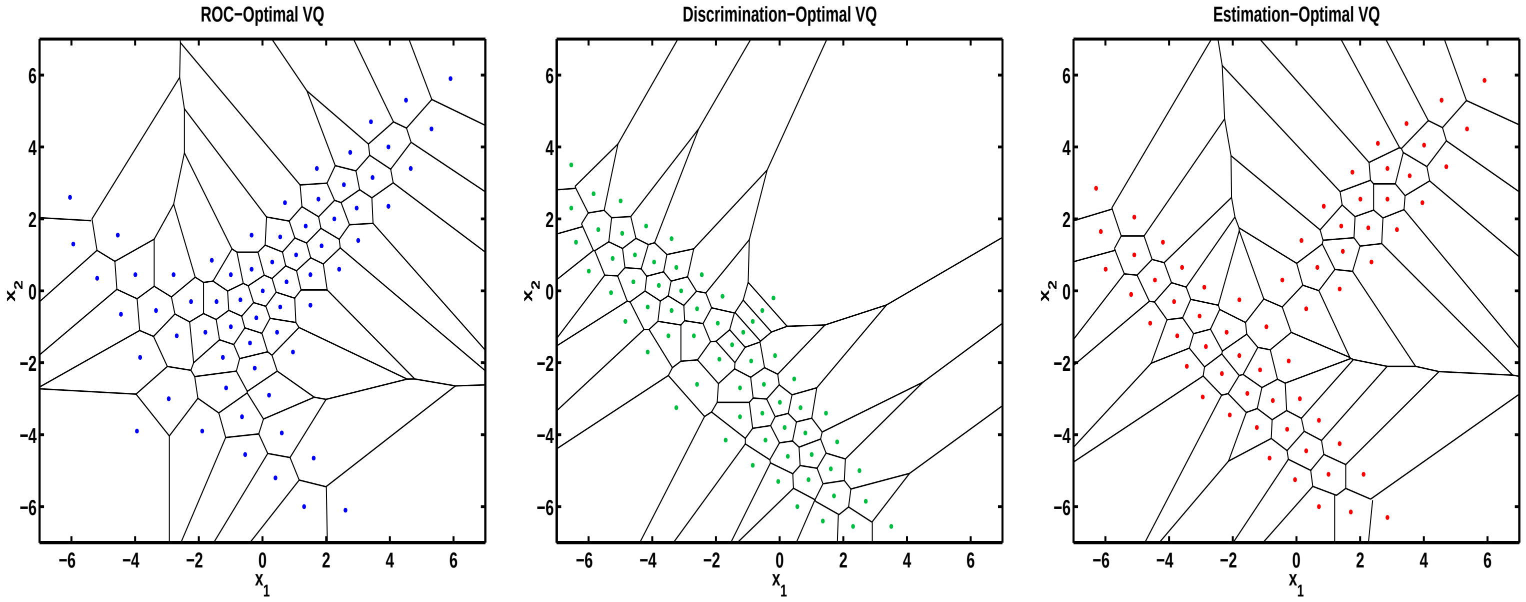


Figure 9. ROC-optimal congruent-cell VQ (left), Discrimination-optimal congruent-cell VQ (middle), and Estimation-optimal VQ (right) with $N = 64$.

LOW POWER STRATEGIES FOR MIMO

Objectives:

- Combat co-channel interference and fading
- Achieve higher data rates for fixed BER
- Assure information security

Previous Work:

- BLAST (Foschini BLTJ96, WPC98)
- Channel capacity Rayleigh fading (Telatar ET98; Marzetta&Hoc
- Sub-optimal Space-Time codes (Seshadri IT98 Hochwald&Marz

Contributions:

- optimal signal design for Rayleigh fading
- Rician fading extensions
- Secure space-time modulation

$$\boxed{X = \eta S H + N, \qquad H = (\sqrt{1-r})G + (\sqrt{rMN})\alpha\beta^{\dagger}}$$

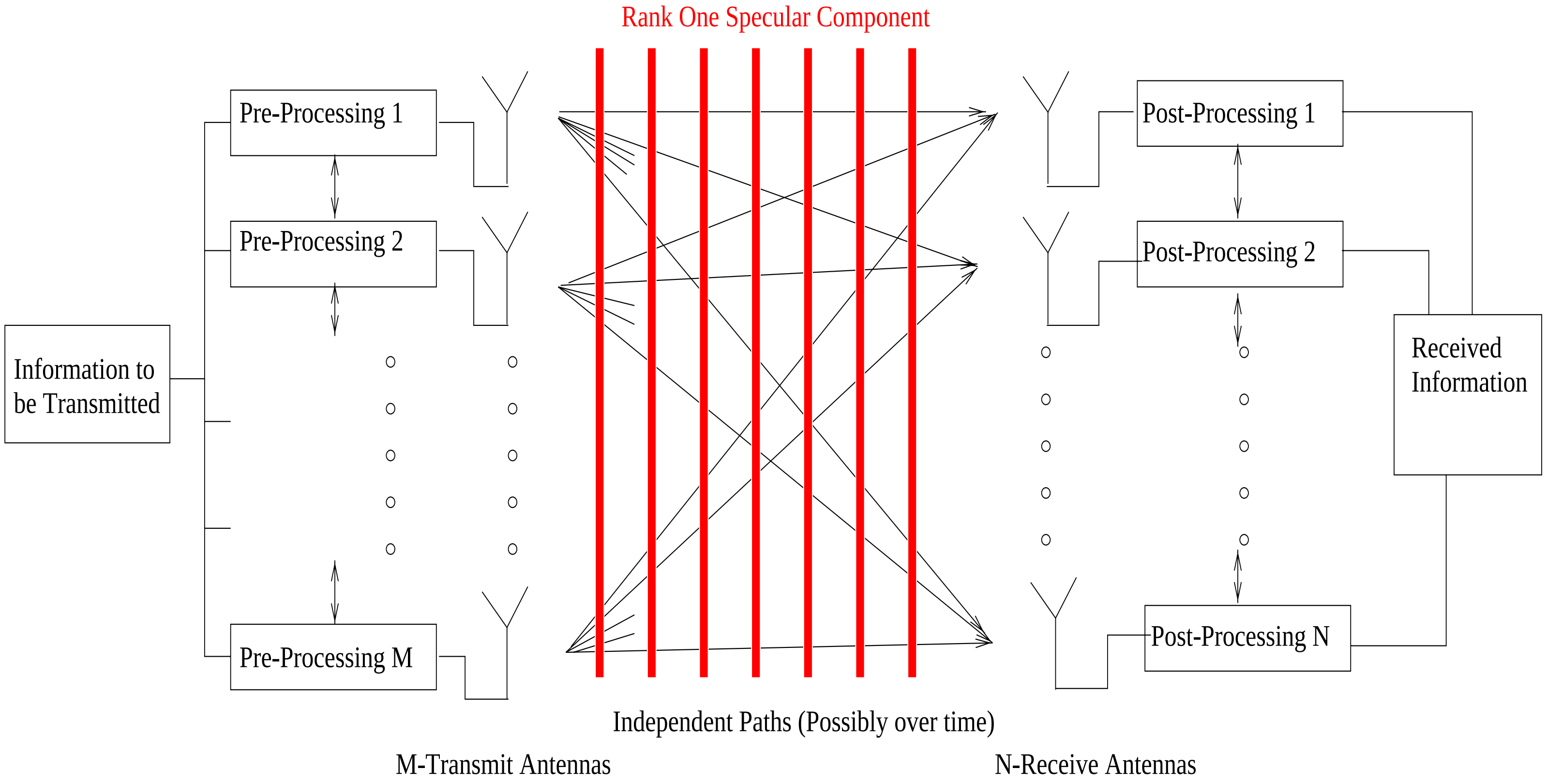


Figure 10. Multiple antenna transmitter and receiver channel. M transmitters, N receivers, T time samples.

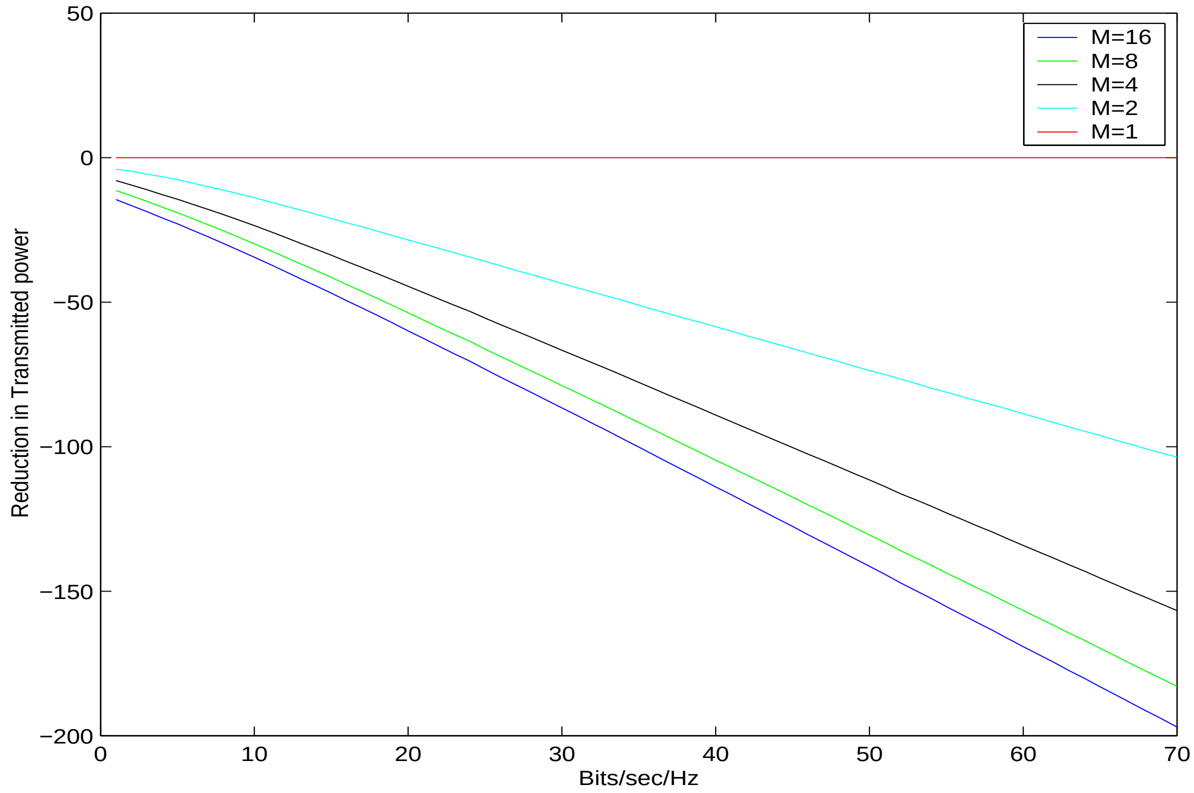


Figure 11. Reduction in Transmitted power for different number of antennas as a function of capacity (bps/hz). Rayleigh fading channel is assumed known by receiver but not by transmitter.

IT-IR Link

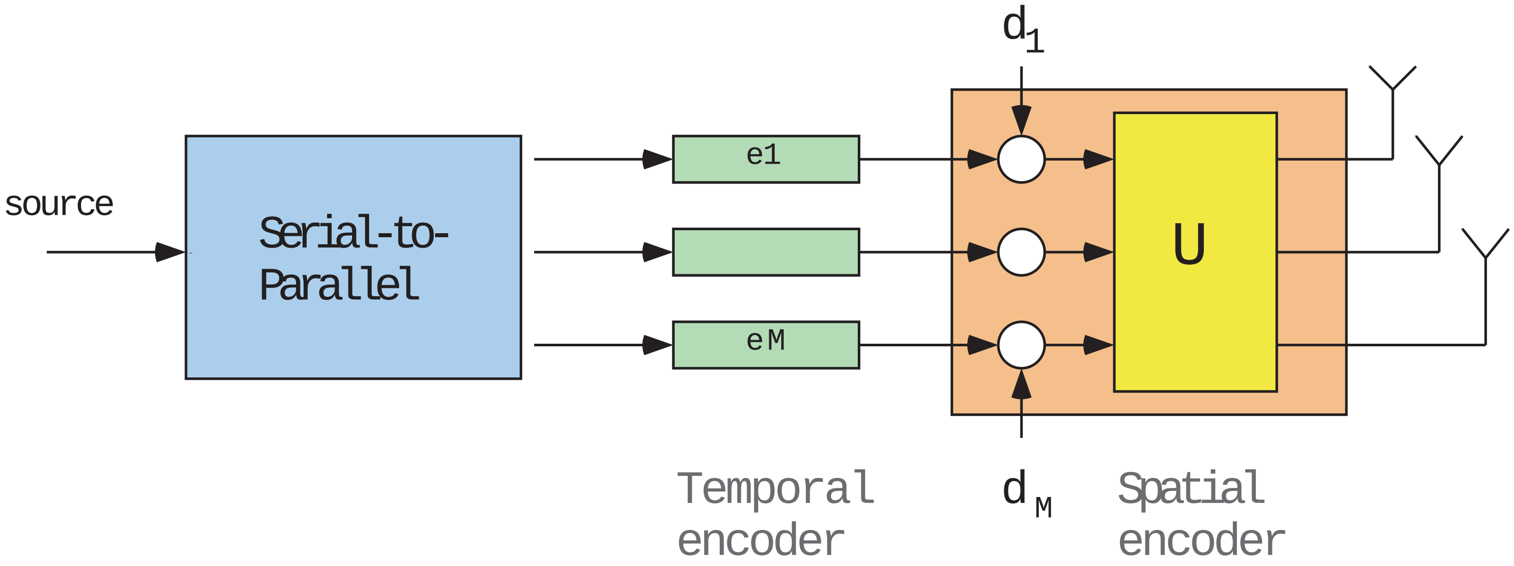


Figure 12. *Optimal STC for informed-transmitter informed-receiver*

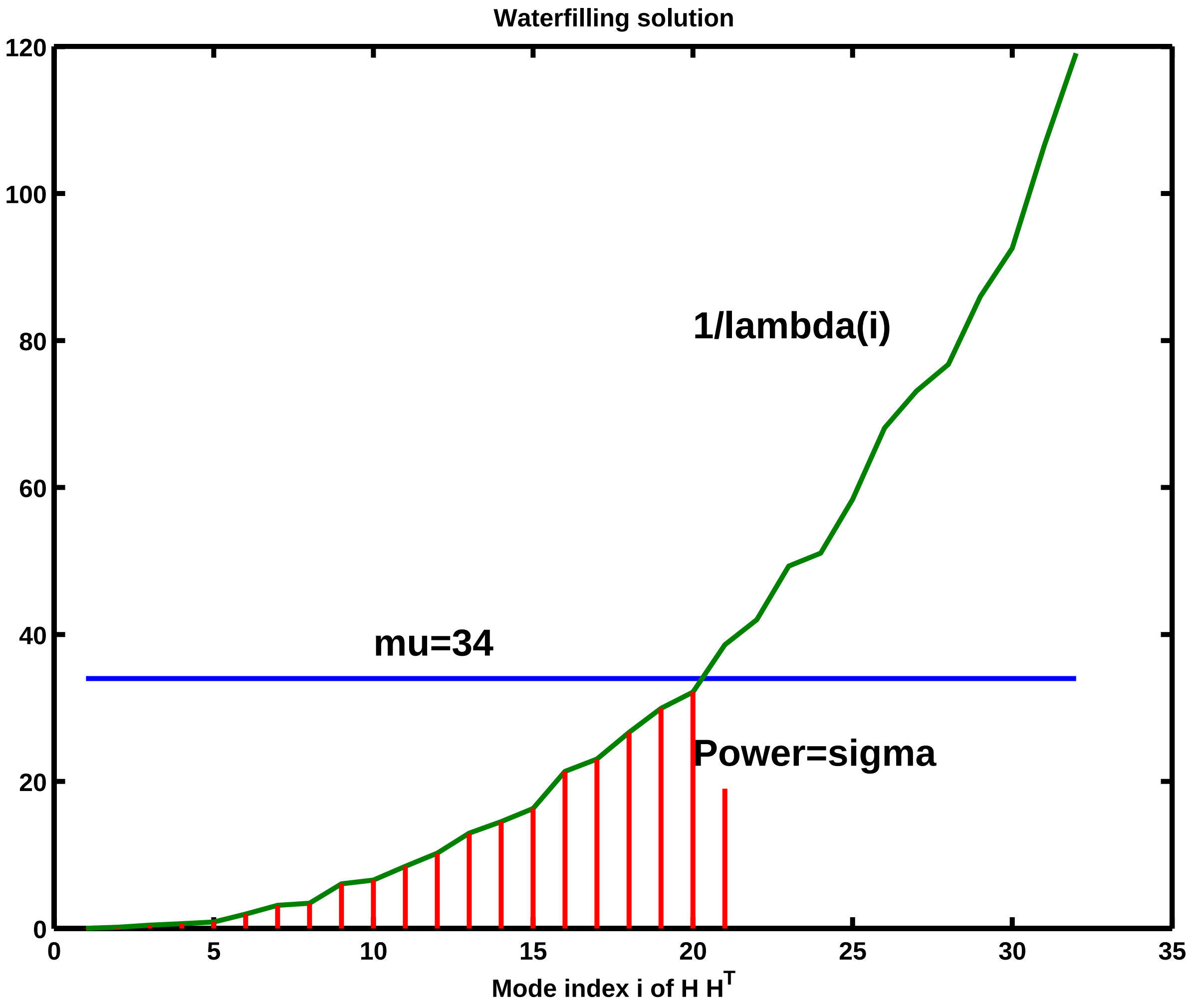


Figure 13. *Waterpouring solution for power-capacity achieving mode allocation*$(N = M = 32)$

UT-IR Link

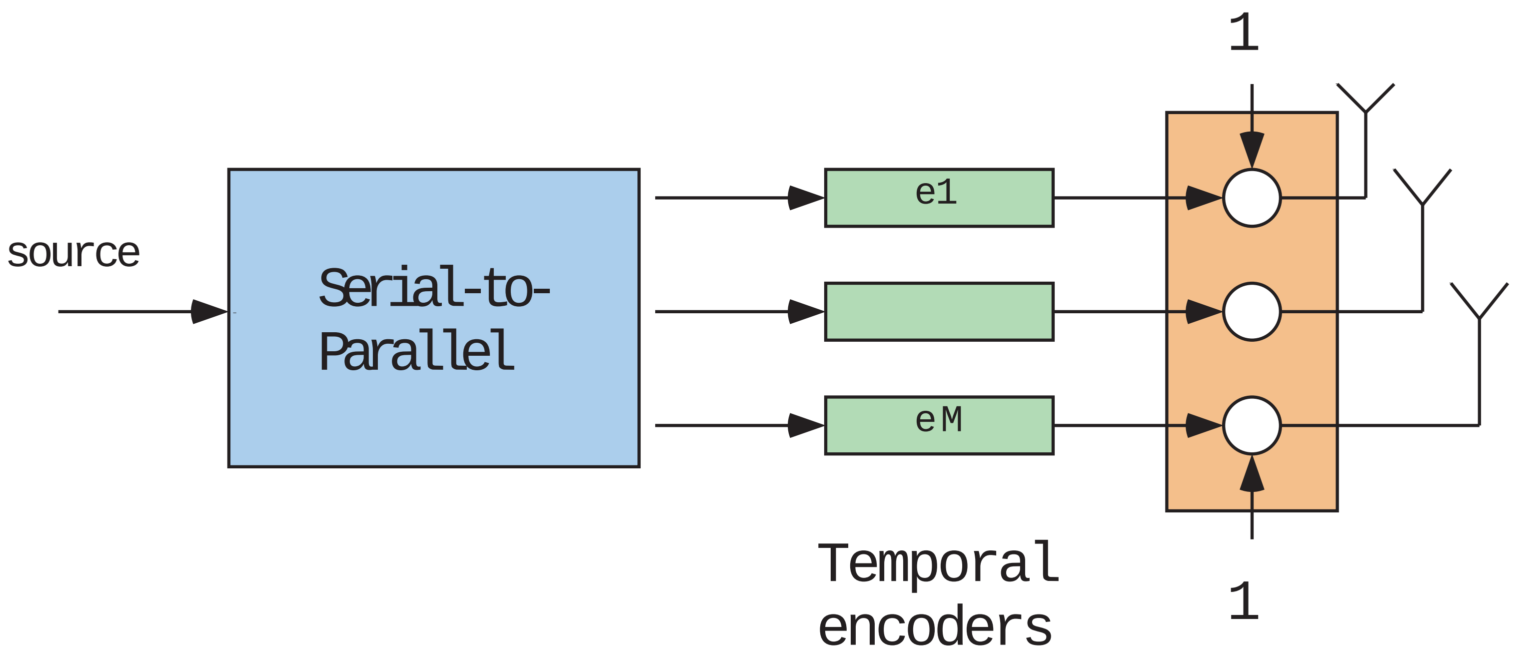
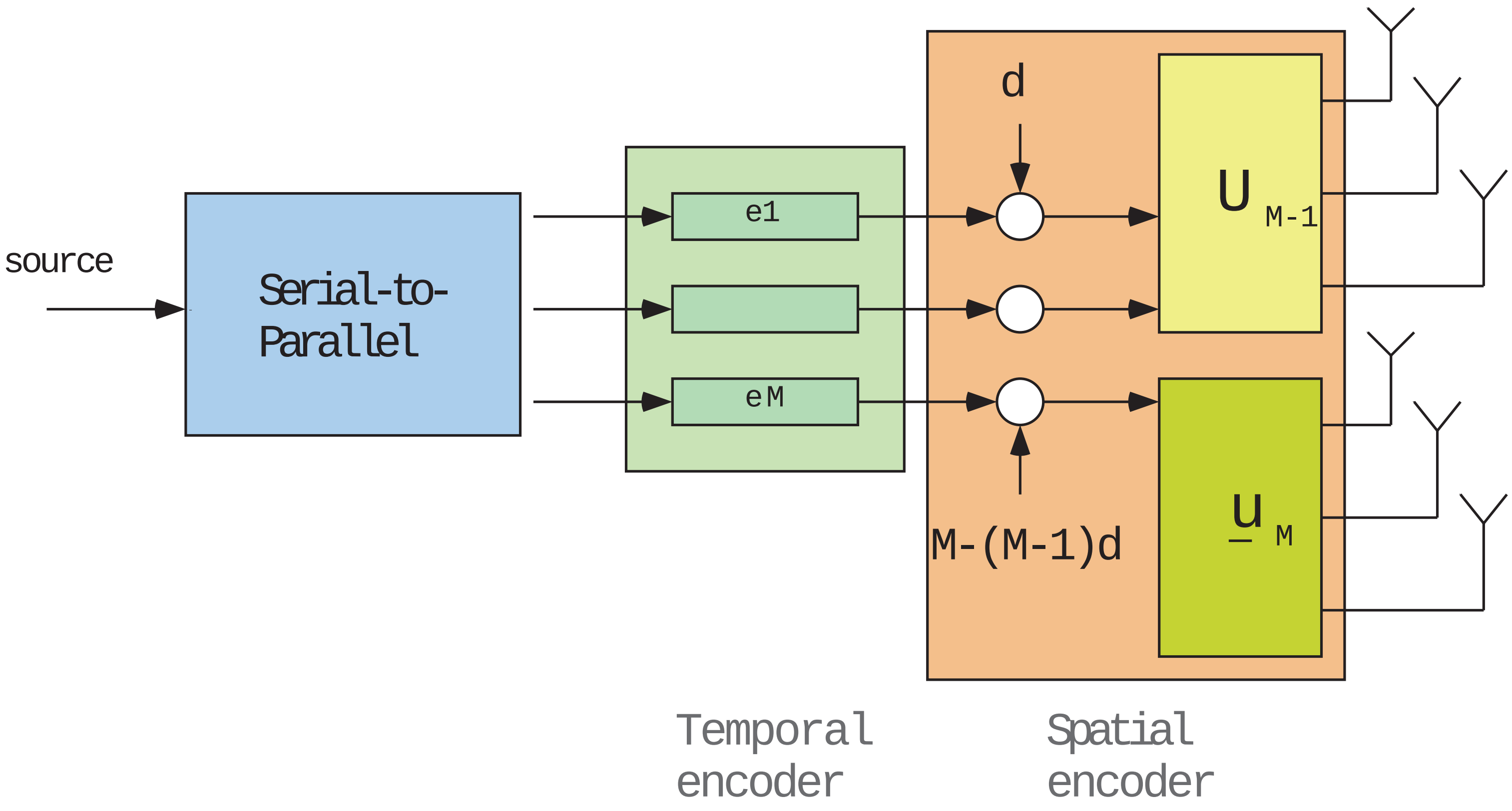


Figure 14. *Optimal STC for UT-IR: Rayleigh link*

Optimal STC for UT-IR: Rician Link



source

Serial-to-Parallel

e1

eM

d

$M-(M-1)d$

U_{M-1}

$\underline{u}_M$

Temporal encoder

Spatial encoder

Figure 15. *Optimal STC for Rician uninformed-transmitter informed-receiver*

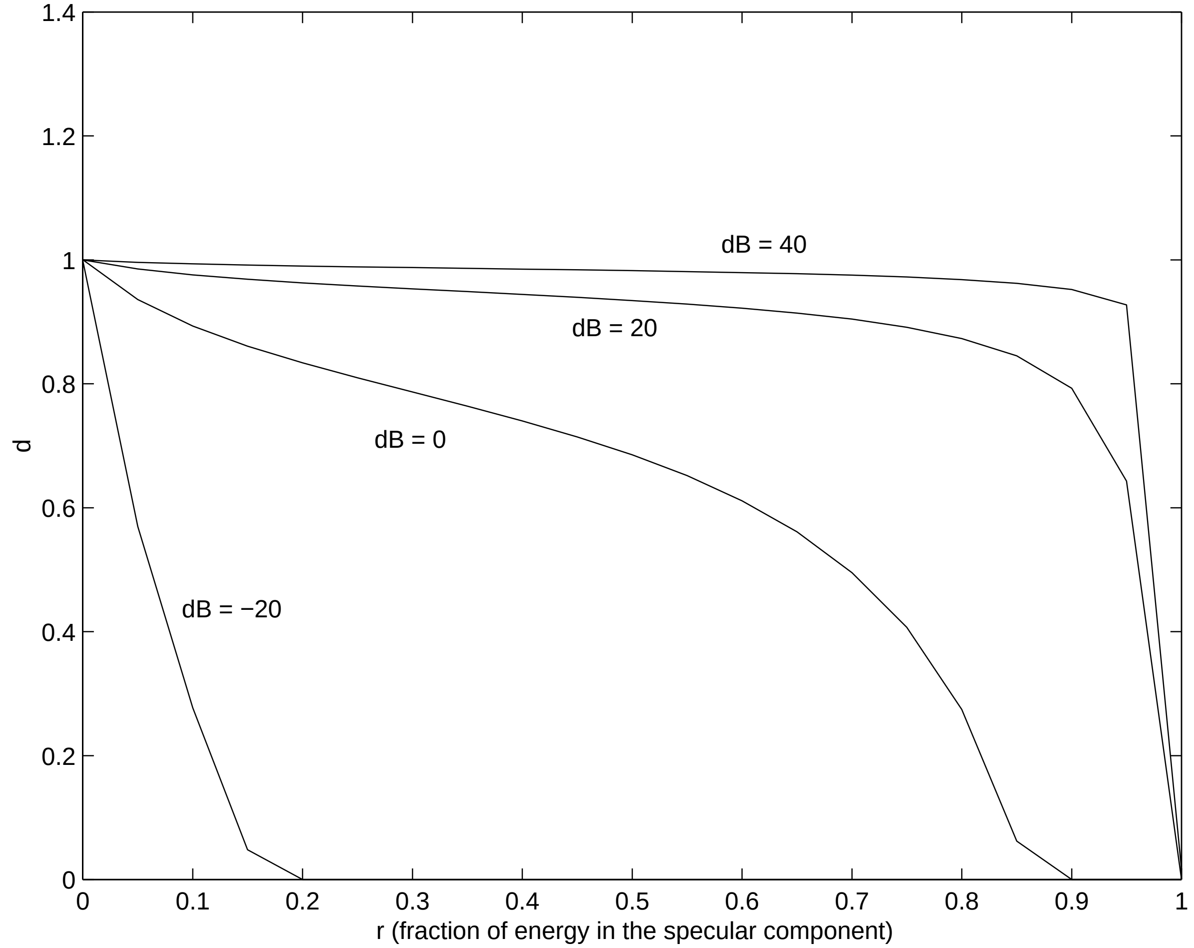


Figure 16. *Numerical optimization yields* $l = 0$ *and values of* d *shown as a function of* r *for different values of* η *(SNR).*

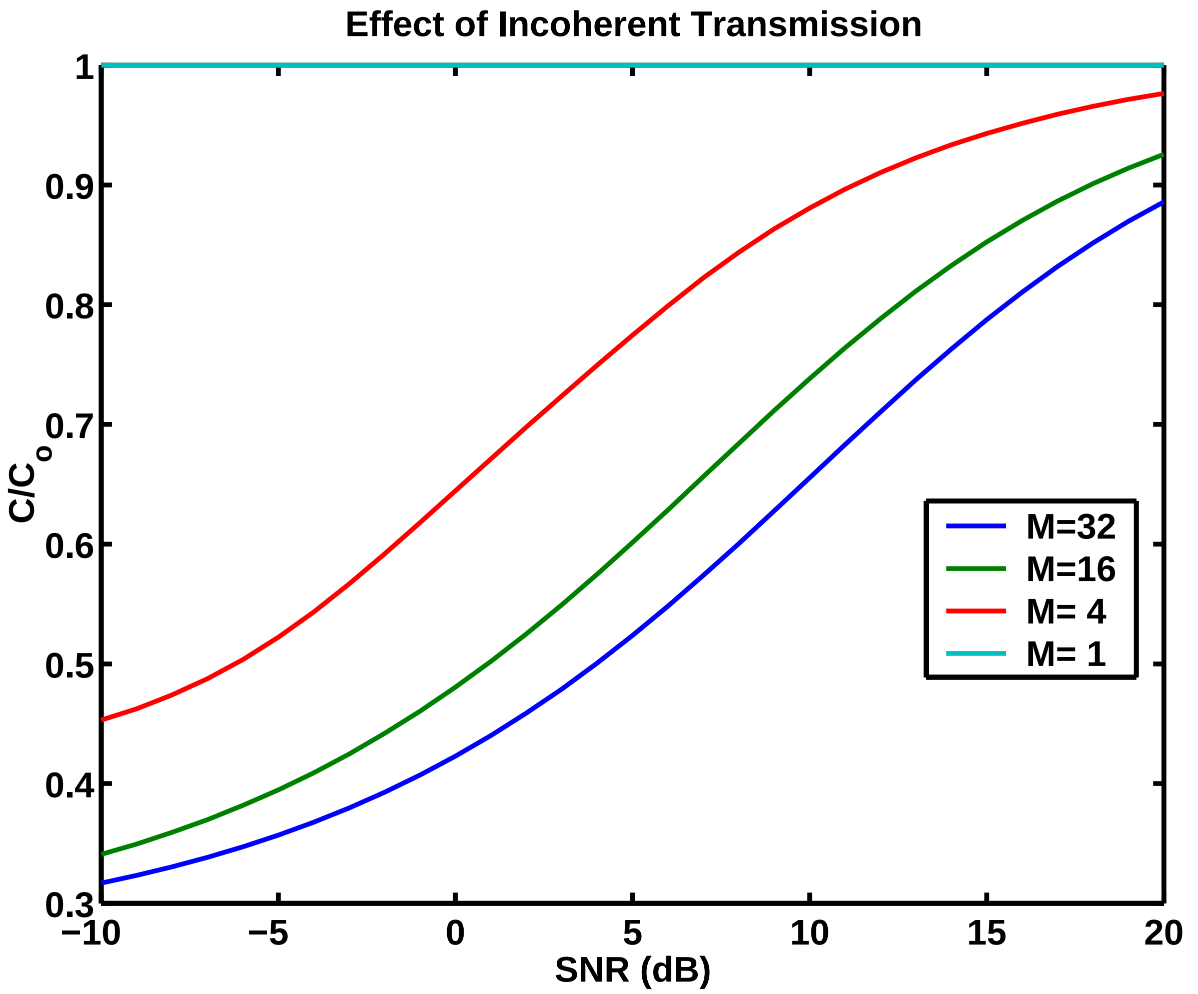


Figure 17. *Capacity loss due to uninformed transmission (UT-IR).*

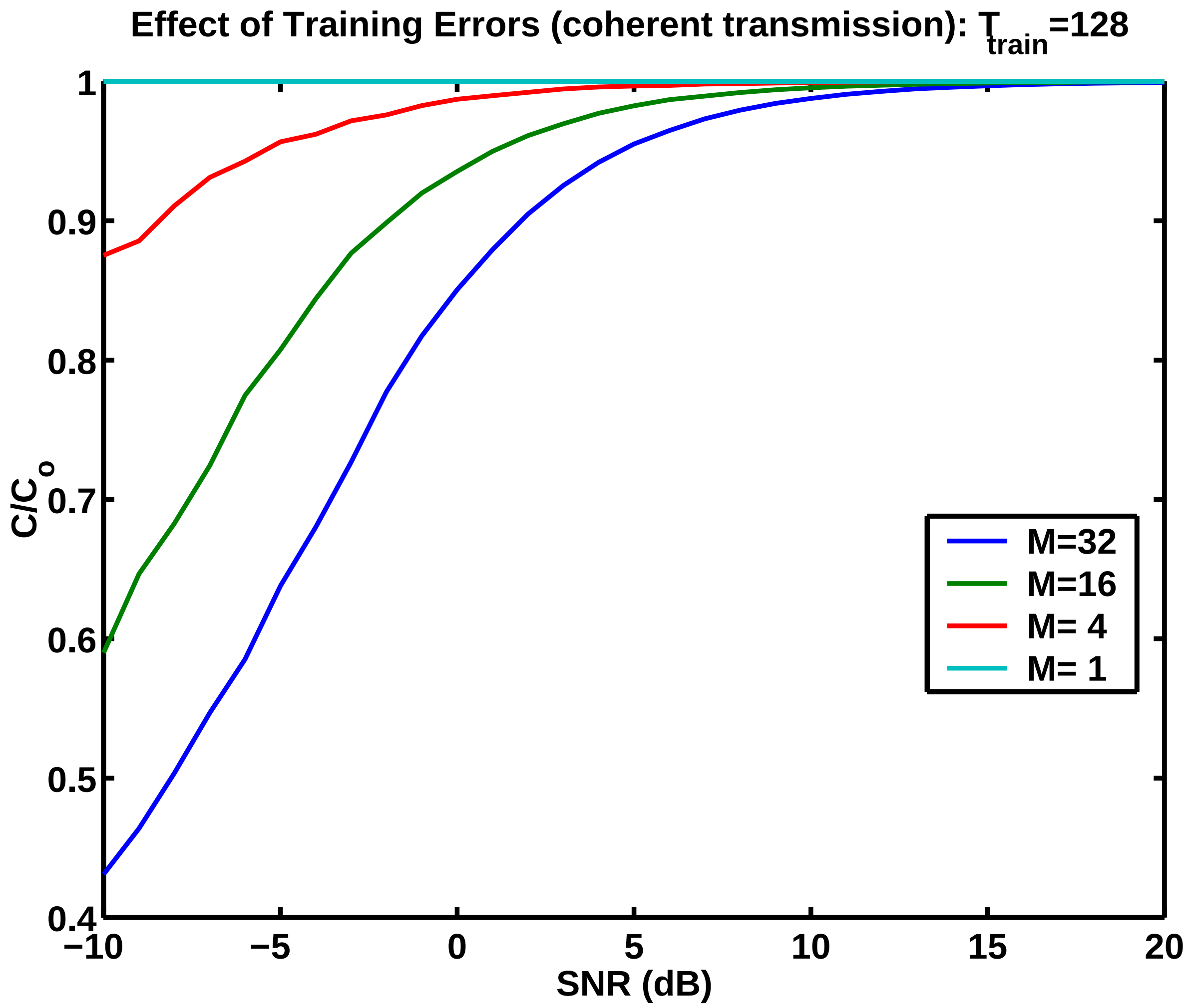


Figure 18. *Capacity loss due to T/R channel estimation errors.*

UT-UR Link

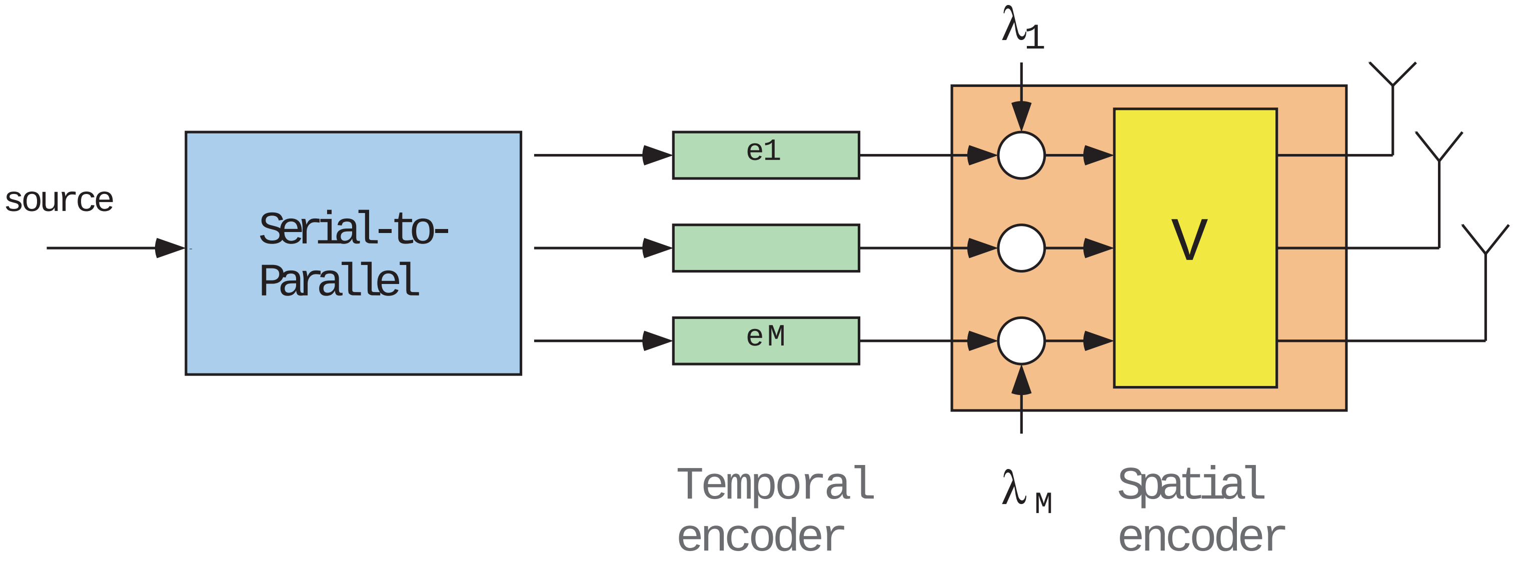


Figure 19. *Optimal STC for uninformed-transmitter uninformed-receiver*

MIMO INFORMATION SECURITY

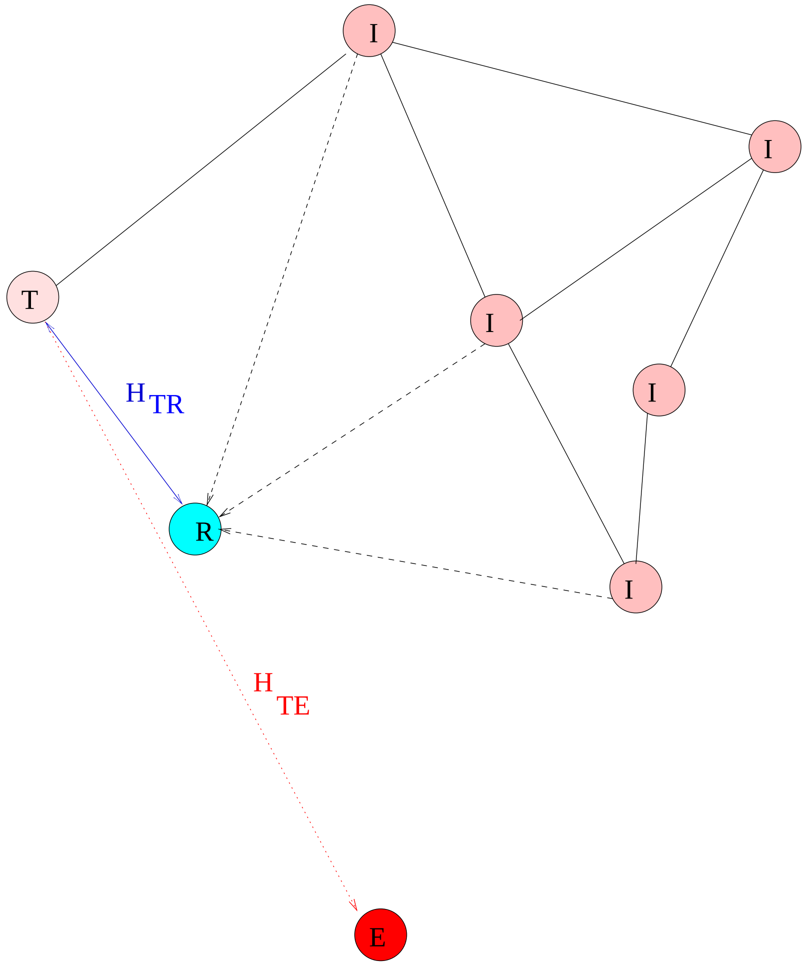


Figure 20. *Wireless network with eavesdropper*

Information Security: Eavesdropper Resistance

Hypotheses:

1. Subscriber links have *informed* transmitters/receivers (IT-IR):
    - H_{TR} is known to both parties over a hop
    - Training generally required to learn channel
    - Feedback required to inform transmitter of channel
2. Eavesdropper link has *uninformed* transmitter (UT)
    - H_{TE} unknown to transmitter
    - S, H_{TE} may be known or unknown to eavesdropper
    - Modulation type, signal constellations, source density, may be known to eavesdropper

LPD constraints

The eavesdropper must make a decision between

$$H_0 : \qquad X_i = W_i, \qquad i = 1, \ldots, L$$

$$H_1 : \quad X_i = S_i H_i + W_i, \quad i = 1, \ldots, L$$

His minimum attainable detection error probability has exponential rate

$$\liminf_{L \to \infty} \frac{1}{L} \ln P_e \quad = \quad \rho$$

$$\rho \quad = \quad \inf_{\alpha \in [0,1]} \lim_{L \to \infty} \frac{1}{L} \ln \int f_{H_1}^{1-\alpha}(X) f_{H_0}^{\alpha}(X) dX$$

- ρ is Chernoff error exponent ($\rho \leq 0$)
- ρ is minimal α-divergence between densities f_{H_1} and f_{H_0}
- Chernoff exponent is achieved for Bayes test

Uninformed Eavesdropper: Low SNR

$$\begin{aligned}\rho &= \min_{\alpha\in[0,1]}\left(-\frac{\alpha(1-\alpha)\eta_e^2}{2}\,\mathrm{tr}\{\overline{SS^\dagger}\;\overline{SS^\dagger}\}+o(\eta_e^2)\right)\\ &= -\frac{\eta_e^2}{8}\,\mathrm{tr}\{\overline{SS^\dagger}\;\overline{SS^\dagger}\}+o(\eta_e^2)\end{aligned}$$

Transmitter strategy:

Attain $E[\max_{P(S)} \ln P(X|H_{TR},S)/P(X|H_{TR})]$ subject to

$$\mathrm{tr}\{\overline{SS^\dagger}\;\overline{SS^\dagger}\} \leq P_{4avg}$$

- Equivalent to constraining S to Gaussian source with

$$\mathrm{tr}\{\overline{SS^\dagger SS^\dagger}\} \leq P_{4avg}/3$$

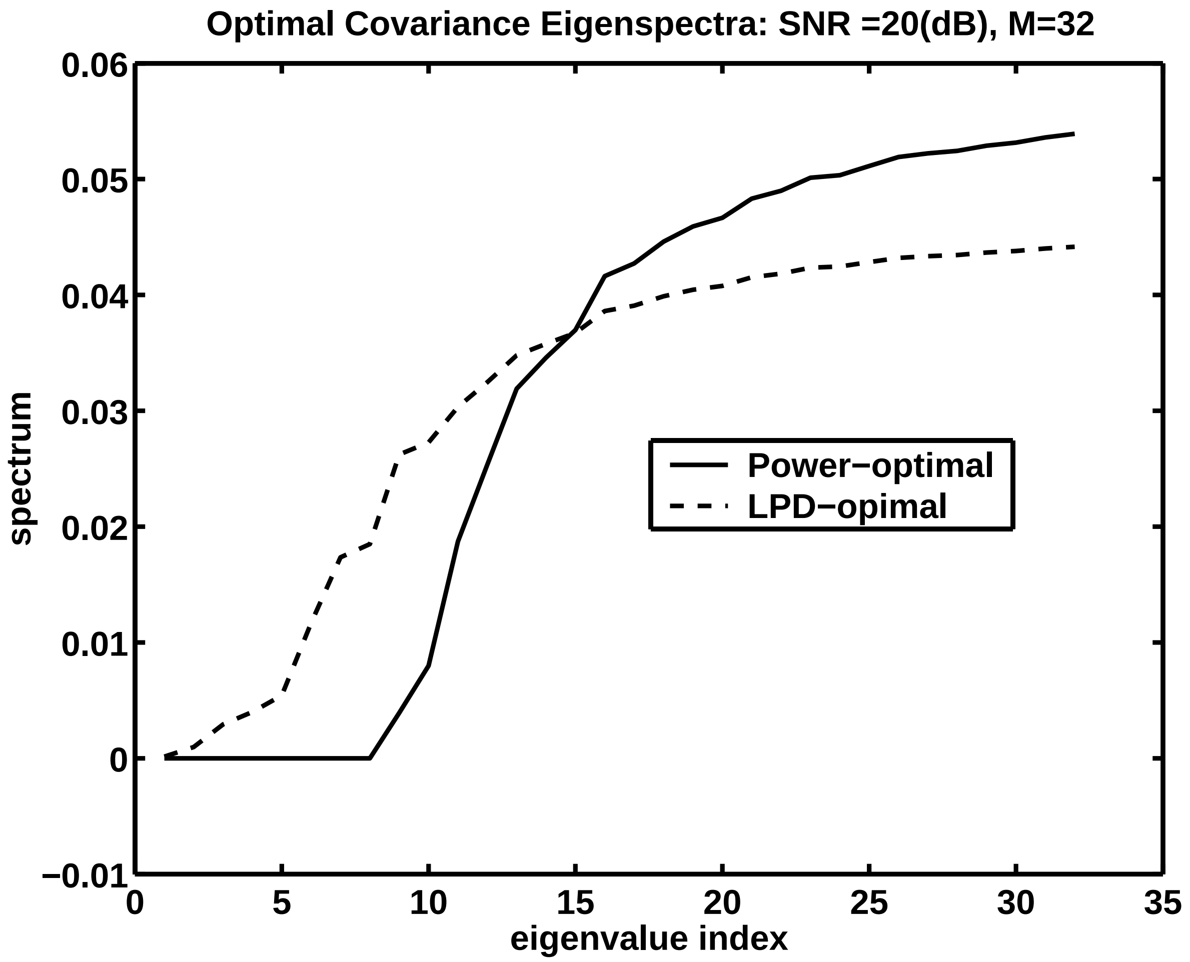


Figure 21. *Optimal source spectra:* $SNR = 20dB, M = N = 32$

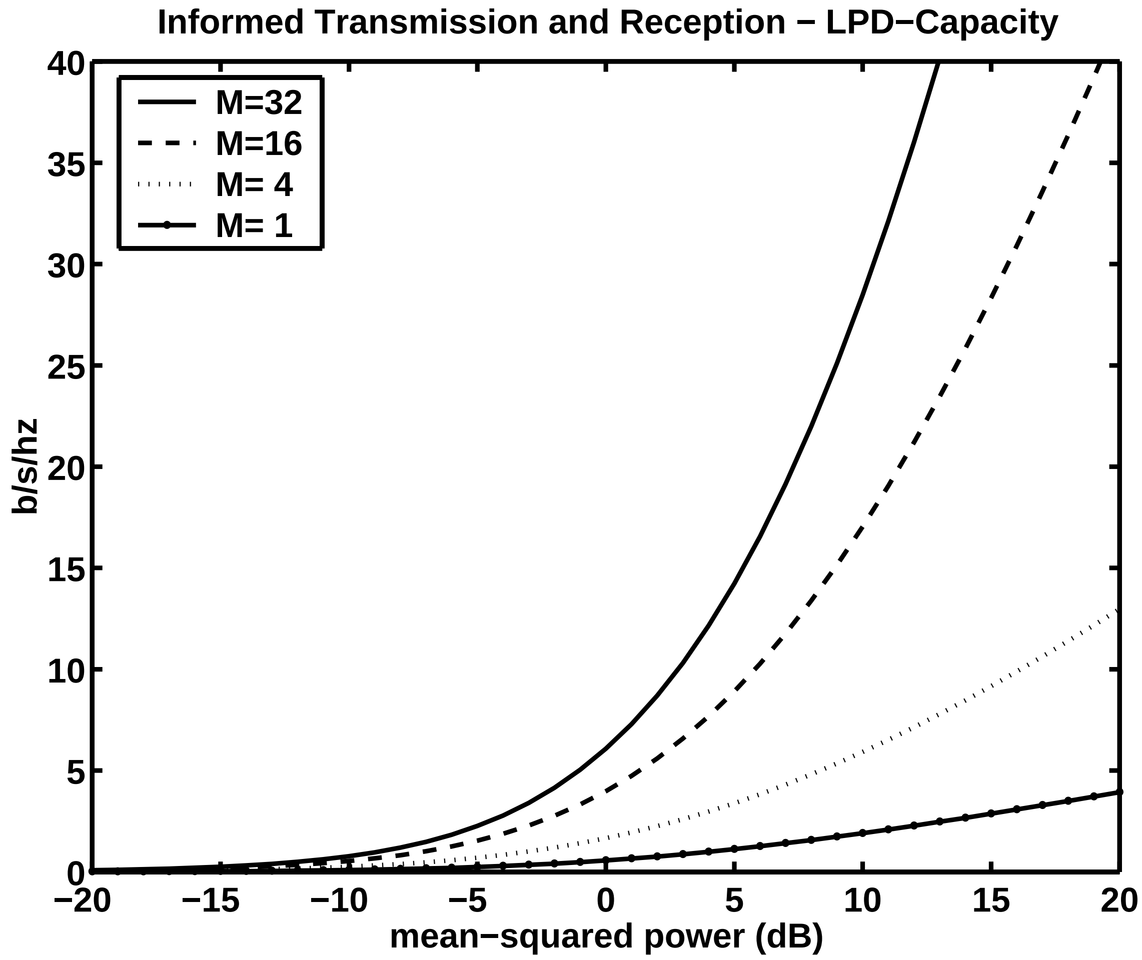


Figure 22. *IT-IR LPD-constrained capacity (N = M)*

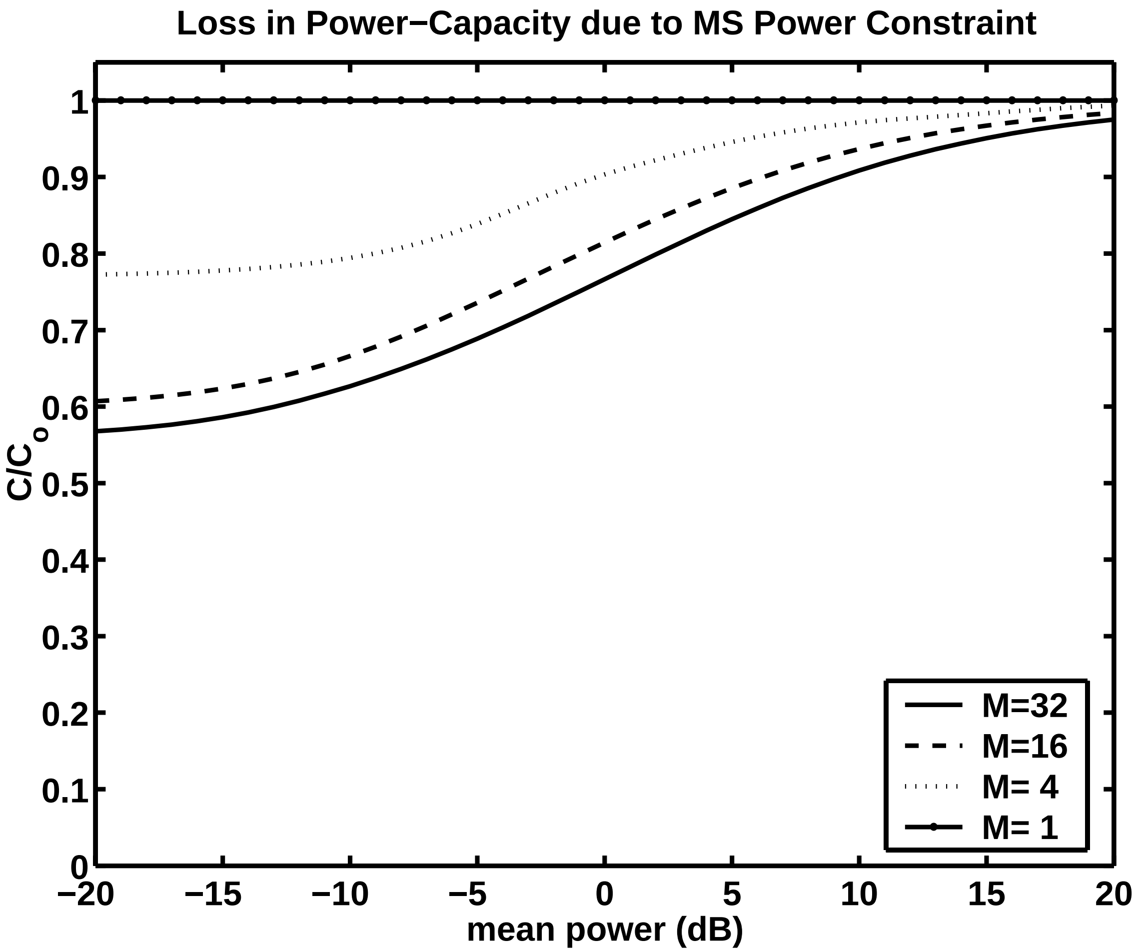


Figure 23. *Loss in power-capacity due to LPD constraint* ($N = M$)

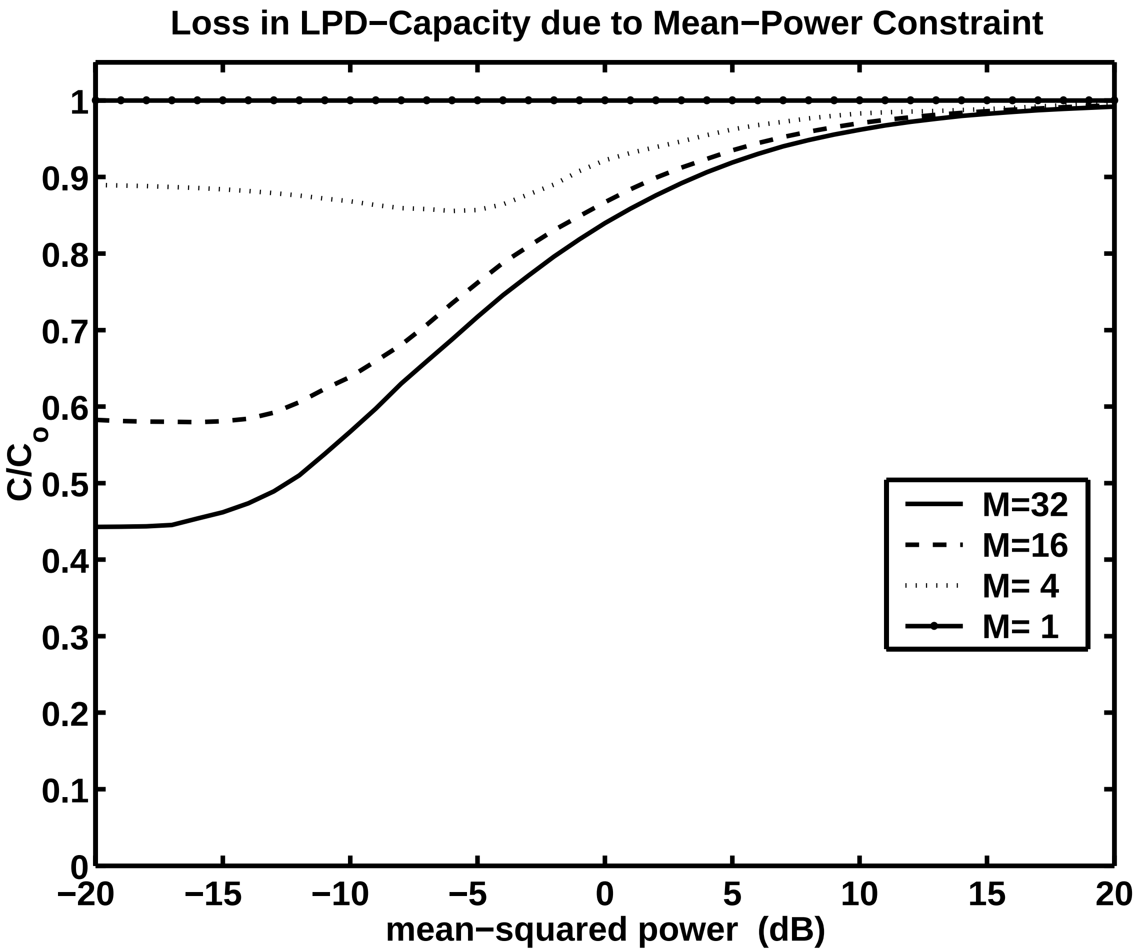


Figure 24. *Loss in LPD-capacity due to Pavg constraint* $(N = M)$

Conclusions

1. Signal processing can greatly impact terminal power consumption
2. Strategies to tradeoff power vs algorithm performance have been developed to optimize
    - Adaptive filter resolution vs convergence rate and steady state error
    - Data compression vs. detection performance
    - MIMO information rates vs. information security
3. Signal processing performance must be considered for maximum power reduction