TU4A-1

Statistical Synthesis of Optimal Coupling Matrix for Robotic Automatic Tuning of Microwave Bandpass Filters

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Outline

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- Statistical Synthesis and Testing Criteria
  A. Statistical Distribution of Coupling Elements
  B. V–curves
  C. Monte–Carlo Analysis
- Verification Example
- Conclusion

Introduction

- Deployment of 5G wireless communication systems
- Tuning of microwave filters
  - major factor in the production cost
- Enhancing the tuning efficiency in mass production
- Filter synthesis as a statistical problem
- Yield optimization[1]
  - requires good physical intuitive initial values

[1] J.W. Bandler and S.H. Chen, "Circuit optimization: the state of the art," IEEE Trans. Microwave Theory Tech., vol. 36, 1988, pp. 424-443.

Introduction

- Mimicking the statistical tuning process of human
- Monte-Carlo optimization
- Statistically optimal Coupling Matrix (CM)
  - –viable physical design
  - –efficient tuning process in mass production
- Infinite number of CMs that meets a given specification
- CM with equi-ripple return loss (RL) [2]
  - –more vulnerable to the tuning error

[2] R. J. Cameron, C. M. Kudsia, and R. R. Mansour, Microwave Filters for Communication Systems. New York: Wiley, 2007, ch. 6–8.

Introduction

- Robotic automatic tuning (RAT)
  - filter model extraction techniques [3]-[5]
  - mechanic error
  - extracted CM and target CM[6]
- Statistically optimal Coupling Matrix
  - center of “Disneyland”

[3] P. Harscher, R. Vahldieck and S. Amari, "Automated filter tuning using generalized low-pass prototype networks and gradient-based parameter extraction,"IEEE Trans. Microw. Theory Techn., vol. 49, no. 12, pp.2532-2538, Dec. 2001.
[4] G. Macchiarella and M. Santoniccolo, "An Original Technique for Computer-Aided Tuning of Microwave Filters," 31st Eur. Microw. Conf., 2001, pp. 1-4.
[5] M. Meng and K.-L. Wu, “An analytical approach to computer-aided diagnosis and tuning of lossy microwave coupled resonator filters,” IEEE Trans. Microw. Theory Techn., vol. 57, no. 12, pp. 3188–3195, Dec. 2009.
[6] P. Zhao, K.-L. Wu, “Model-Based Vector-Fitting Method for Circuit Model Extraction of Coupled-Resonator Diplexers”, IEEE Trans. Microw. Theory Techn., vol. 64, no. 6, pp. 1787-1797, June 2016.

Statistical Distribution of Coupling Elements

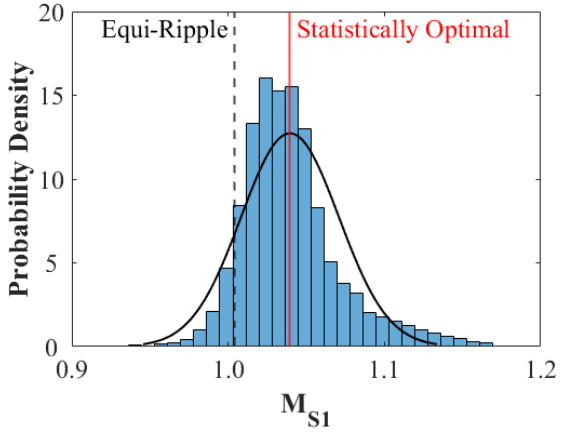
- Statistical Distribution
  - collect as many CMs as possible
  - just satisfies the given specification
- Non-linear optimization
  - emulates the human tuning process
  - just meets the tuning/design specification
  - tuning specification vs. acceptance specification

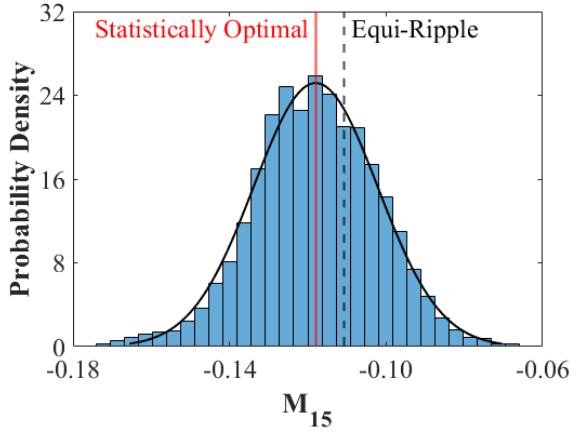
Statistical Distribution of Coupling Elements

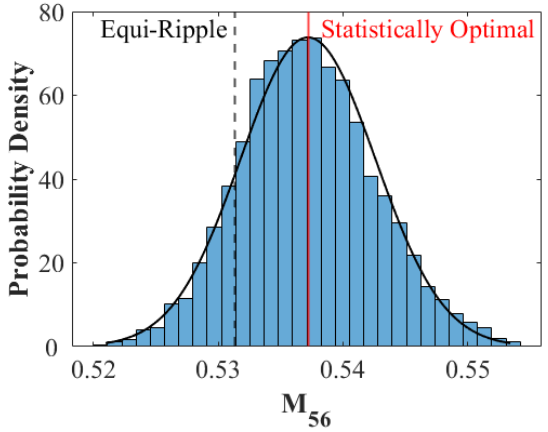
- Monte-Carlo optimization
  - $solve: \min_{x} \max_{i} F_i(g(x))$

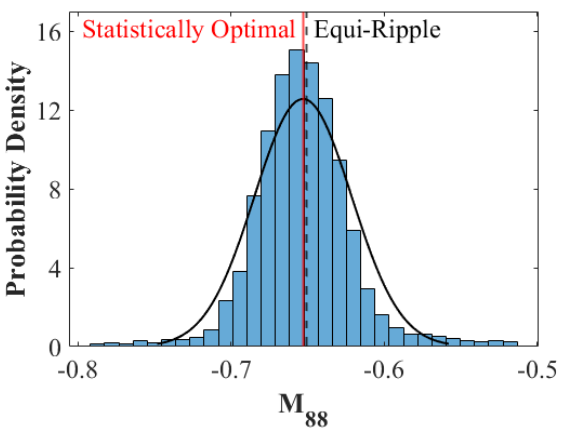
g(x) : insertion and return loss

F(·) : objective function







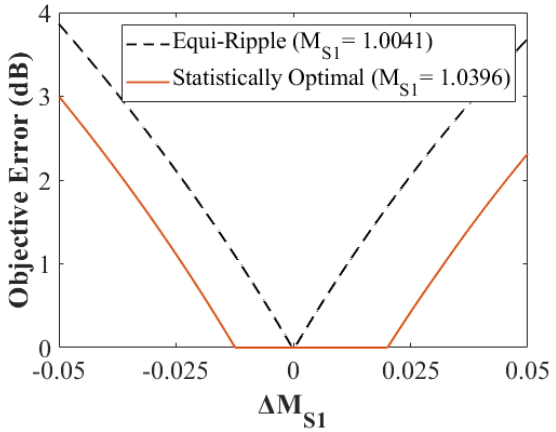


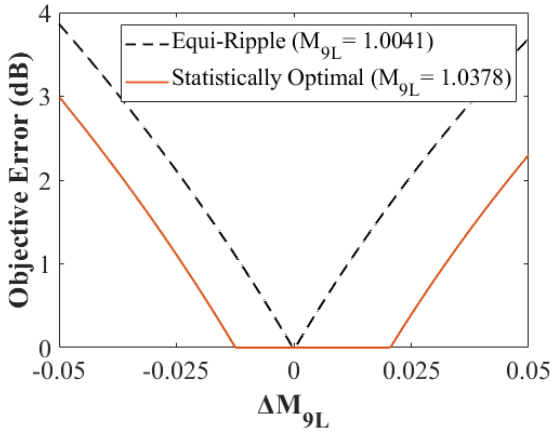
V-curves

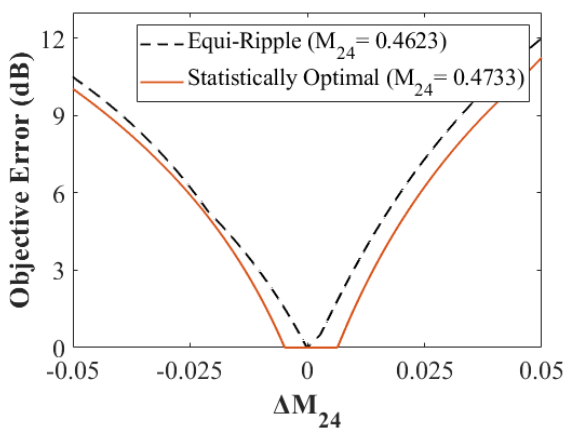
- Sensitivity analysis of each coupling element

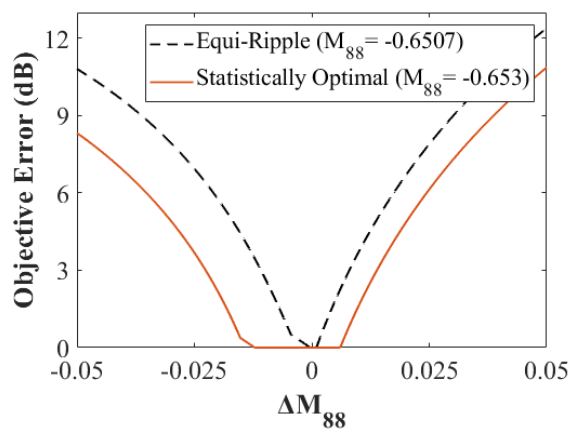
$$-Err = \max_i \boldsymbol{max}(\boldsymbol{g}(\boldsymbol{x}) - \boldsymbol{z}, \boldsymbol{0})$$

$\boldsymbol{z}$: design specification







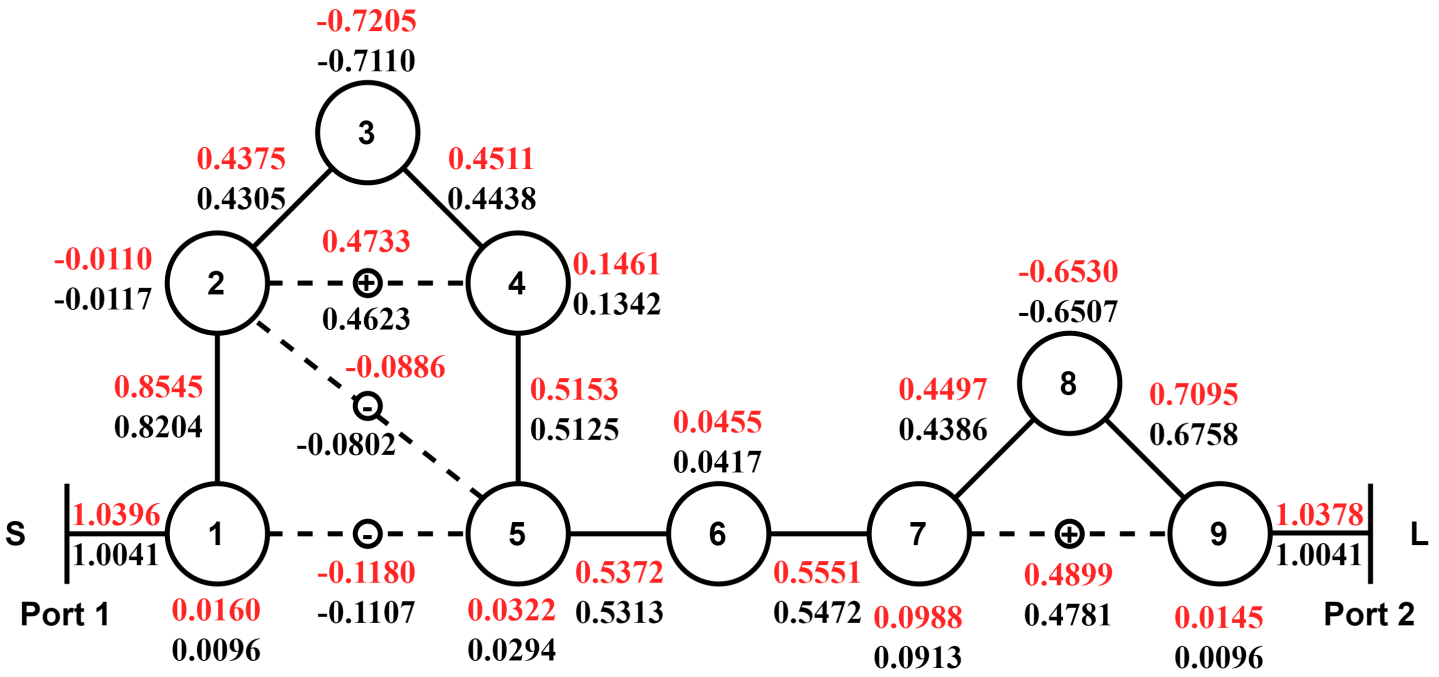


Monte-Carlo Analysis

- Overall sensitivity analysis of a given CM
- Tolerance analysis of microwave filters
- Uniformly distributed random variables
- Estimated yield
  - acceptance specification

Verification Example

- 9th-degree filter with 4 transmission zeros (TZs)

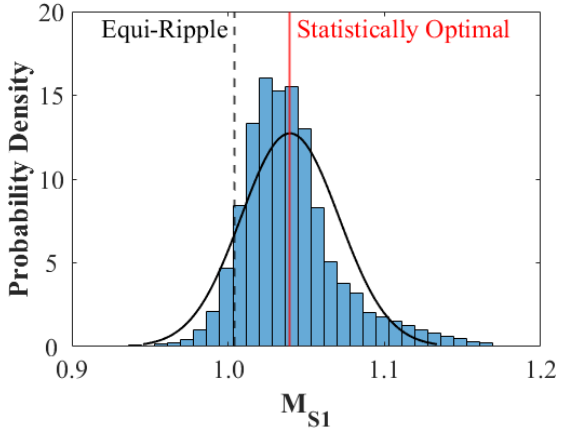


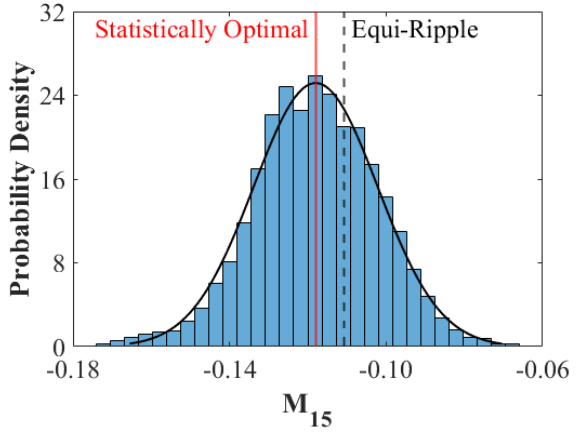
Red: Statistically Optimal CM

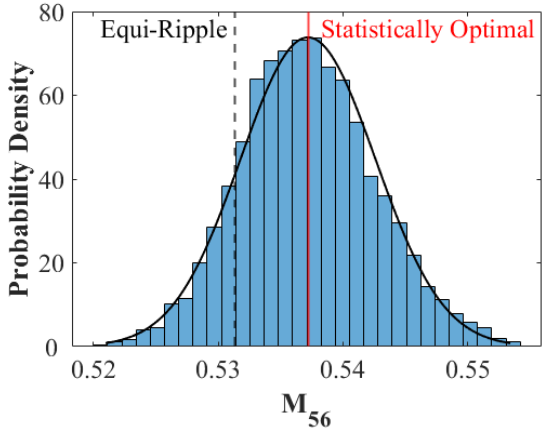
Black: Equi-Ripple CM

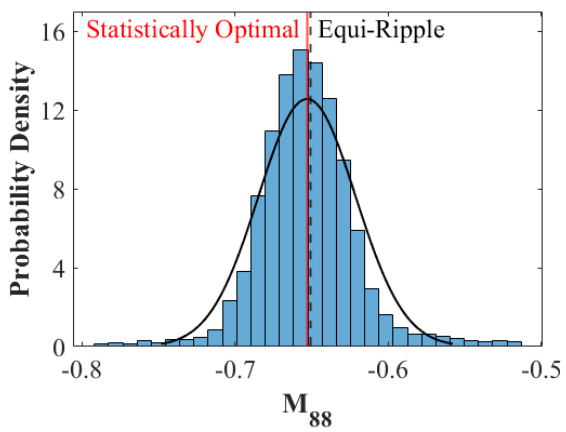
Verification Example

- Statistical Distribution
  - –5000 optimized samples
  - –± 0.05 of the initial values (uniform distribution)
  - – normal distribution



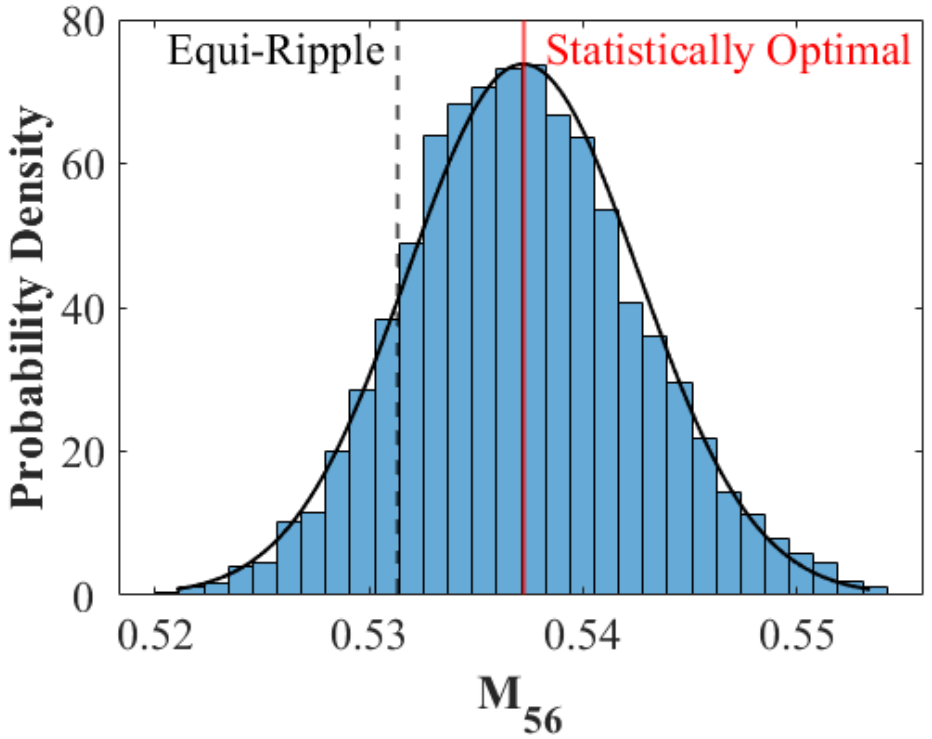






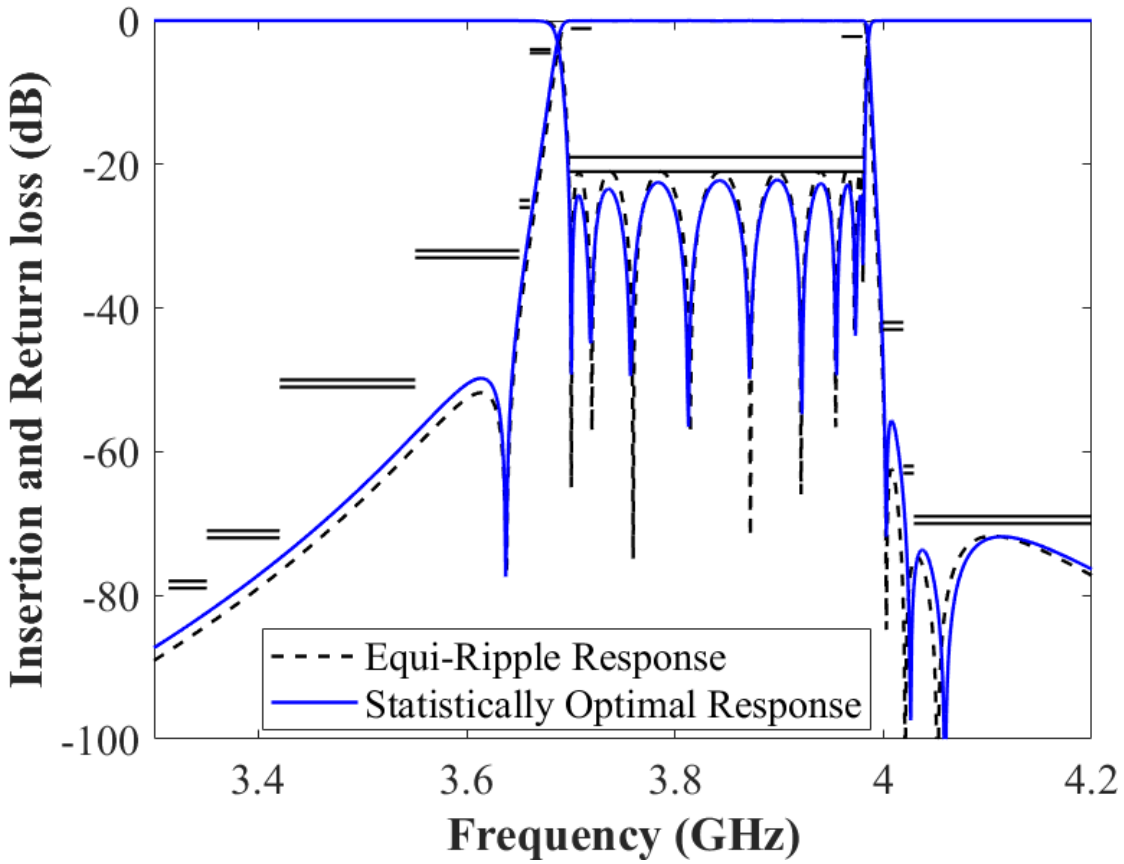
Verification Example

- Statistically Optimal CM
  - optimal value (mean)
  - highest probability density
- Equi-Ripple CM
  - far away from the optimal
  - not optimal for the ease of tuning



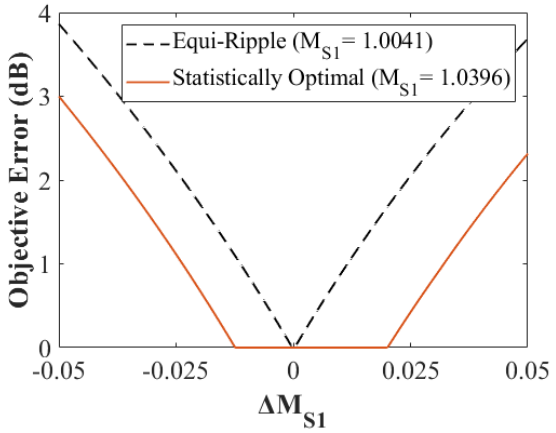
Verification Example

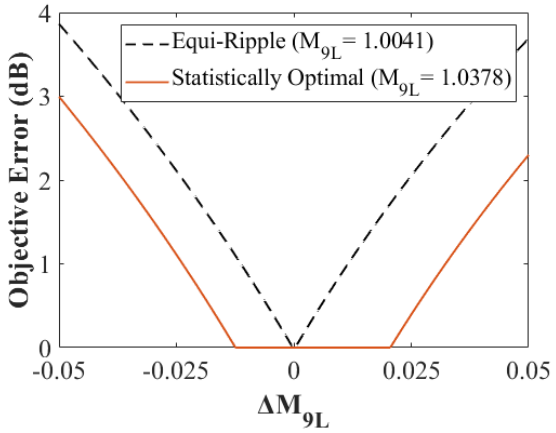
- Equi-Ripple response vs. Optimal response

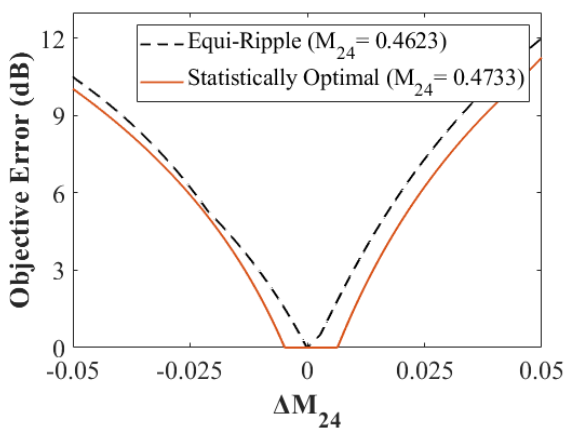


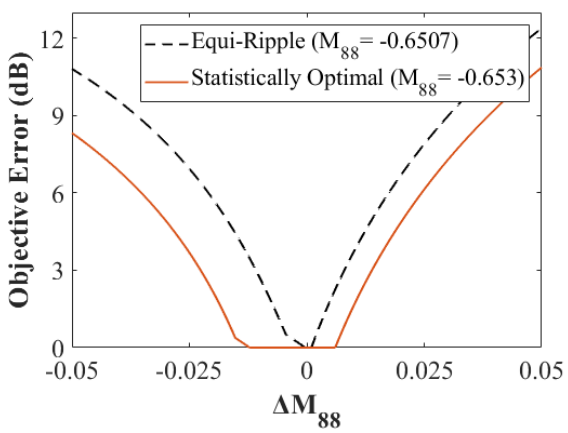
Verification Example

- V-curves
  - zero-error regions
  - relatively gradual slope



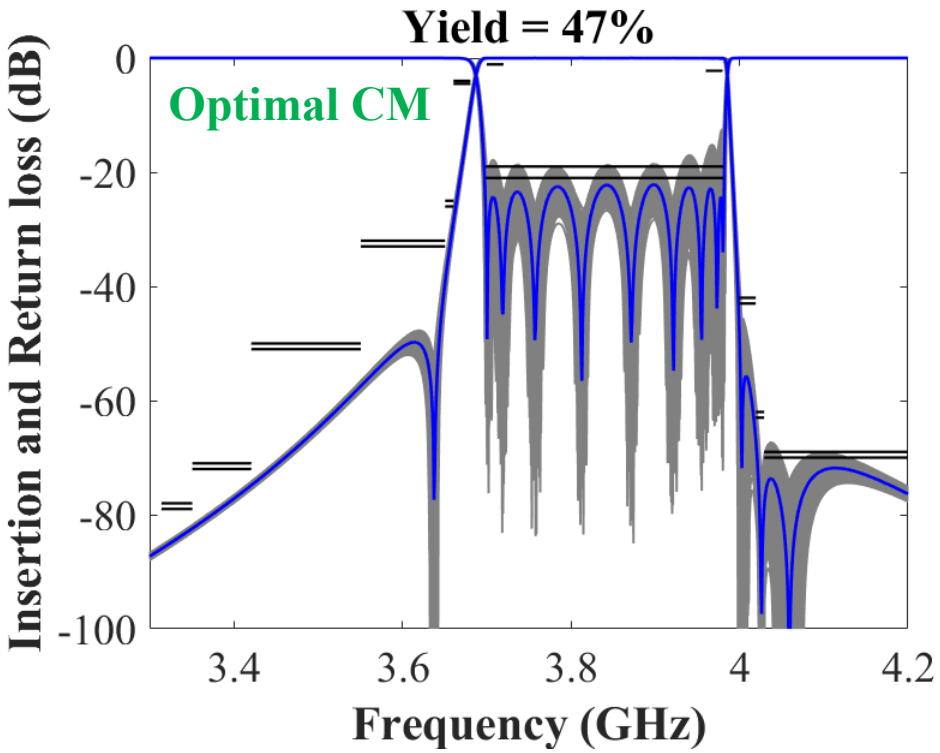


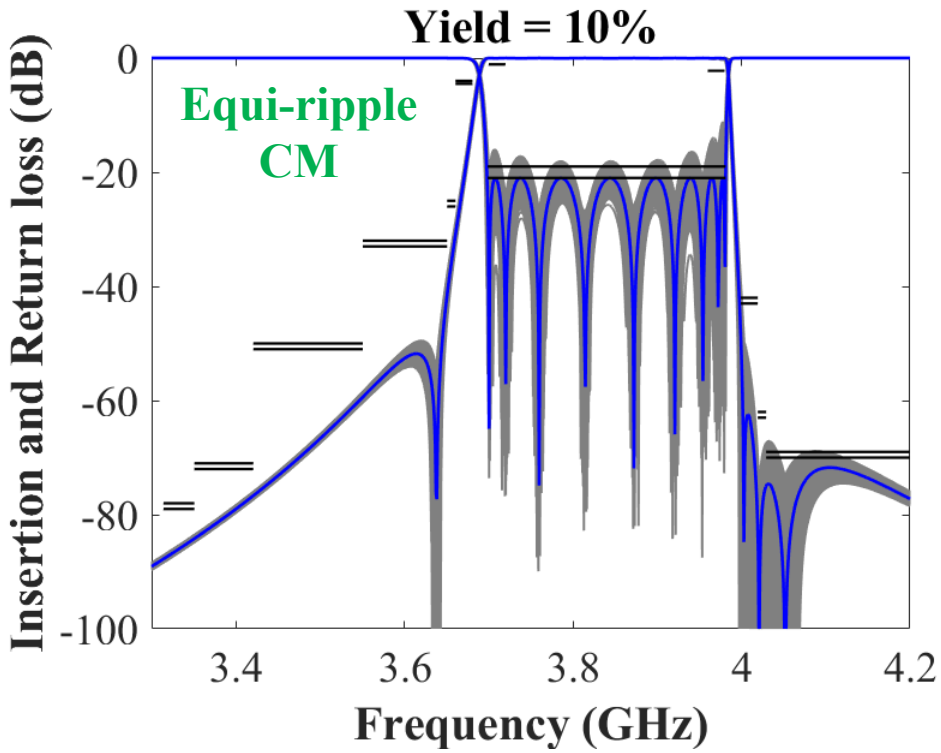




Verification Example

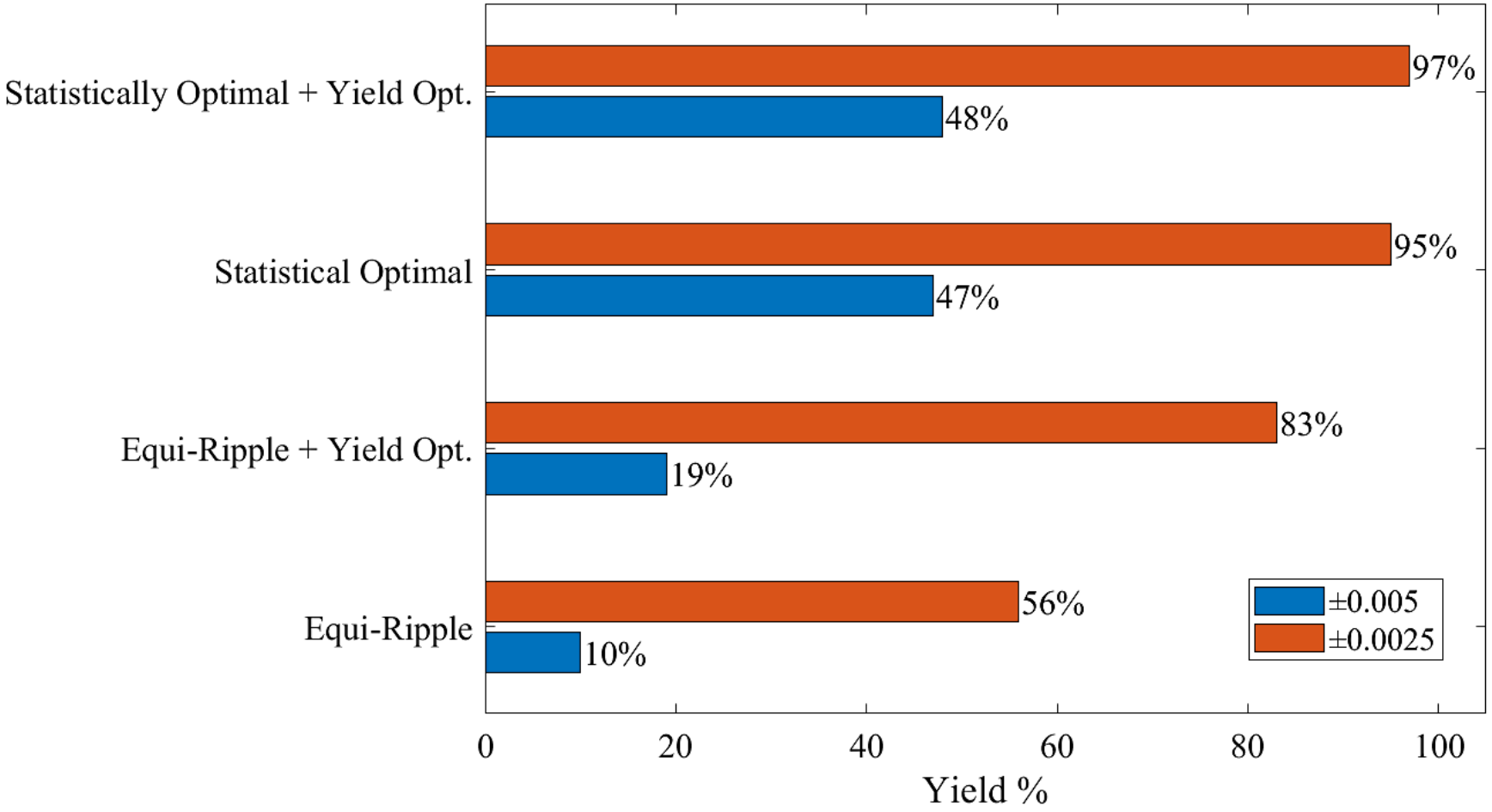
- Monte-Carlo simulation
  - 10,000 samples, ±0.005





Verification Example

- Monte-Carlo simulation



Conclusion

- Equi-ripple CM is not statistically optimal
- V-curves and Monte-Carlo analysis give further evidence
- Superiority of the statistically synthesized optimal CM