The Use of Loaded Antennas as Scattering Relays for Post-Cellular Networks with Closely Spaced Terminals

Intermediate Presentation, Bernhard Gahr

Supervisor: Yahia Hassan

Professor: Armin Wittneben

Outline

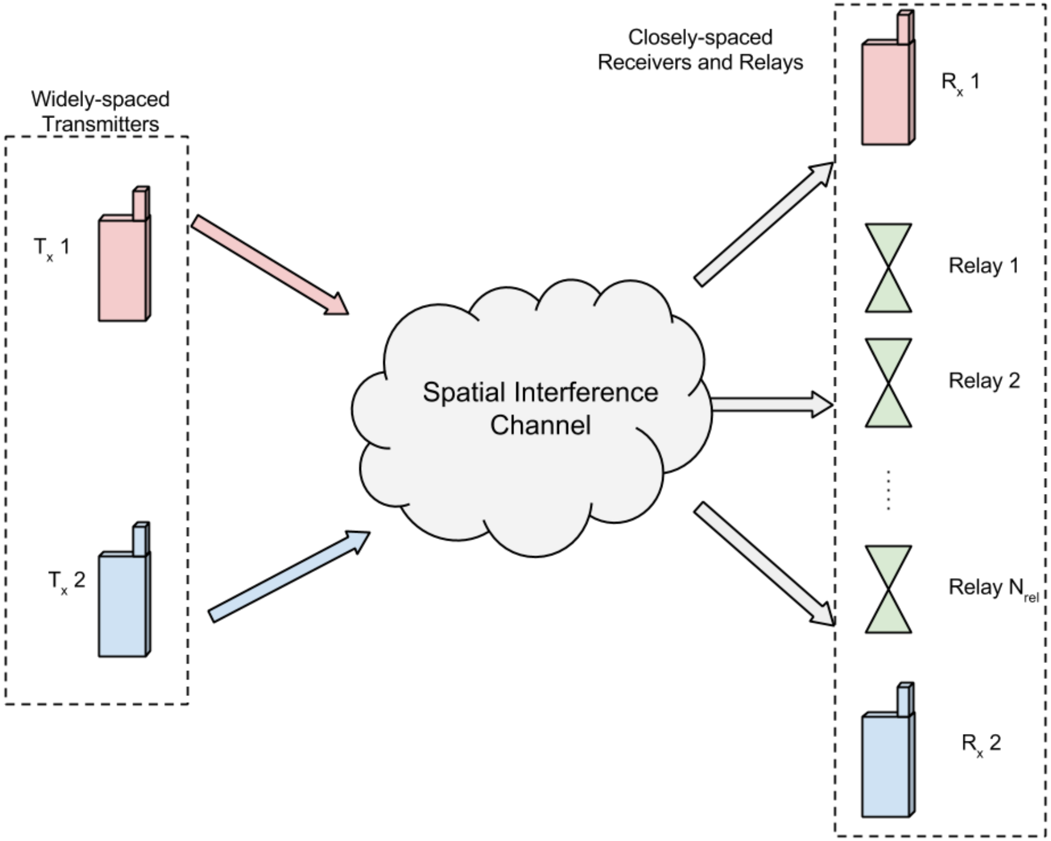
- Motivation
- System Setup
- Receiver - Overview
- Impact of Coupling
- Analysis of Interference
- Cost Function
- Gradient Search
- Simulation Results
- Outlook

Motivation/Problem Description

- Future systems are expected to be characterized by
  - Very high density of nodes (e.g. sensor networks, coverage in stadium)
  - Large number of antennas
  - Lower frequencies
- This leads to closely spaced antennas that are coupled
- One of the most crucial bottlenecks is the interference
- Idea is to improve achievable rates by using *only* passive relays and matching networks
- Coupling between the relays and the receivers is used to minimize the interference.
- Approach of improving the rates is gradient search.

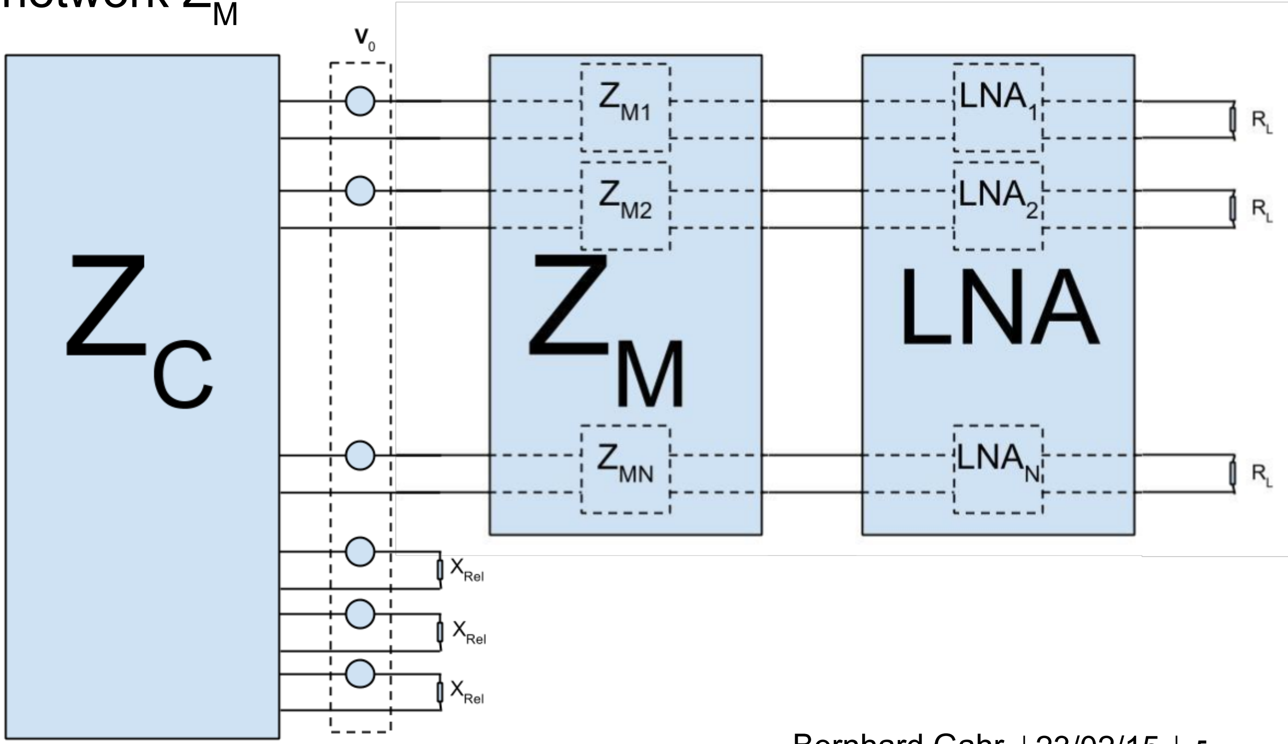
System Setup

- No Coupling between the transmitters
- Coupling between the relays and the receivers
- Passive relays
  - Relays interact only by their coupling
- Connection pairs
  - Rx1 and Tx1
  - Rx2 and Tx2



Receiver - Schematic

- Coupling matrix Z_c
- Open circuit voltages V_o at the antennae
- Uncoupled matching network Z_M
- Low-noise Amplifier
- Further circuitry represented by R_L
- Passive relays represented by pure imaginary X_{Rel}
- 4 Noise sources, in the following only one considered

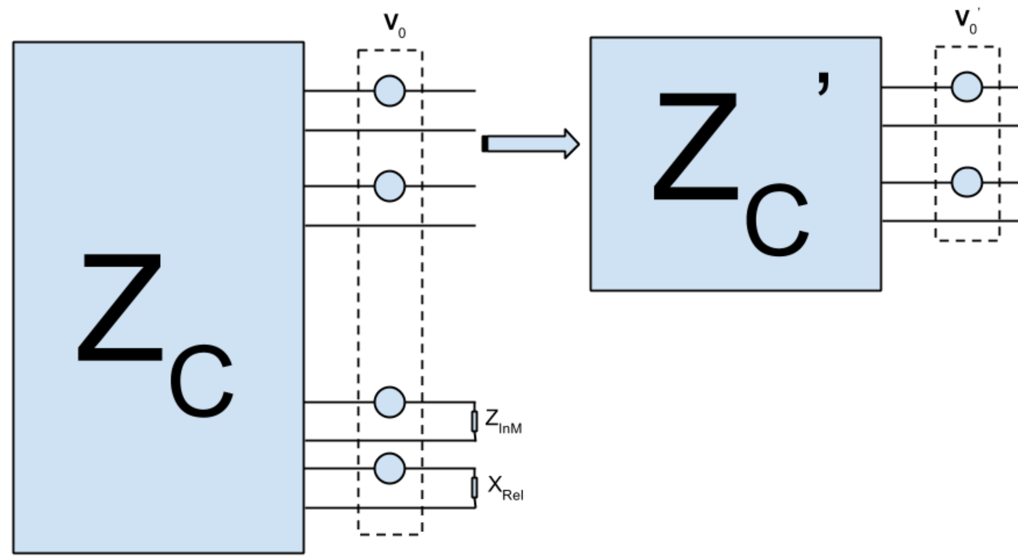


Receiver - Impact of Coupling

- Find an equivalent circuit, with only the required branches
- V'_0 contains the signal at the antenna and the Signal from the coupling

$$\mathbf{v}_0' = \mathbf{H}_0 \cdot \mathbf{v_0}$$

$$\mathbf{H}_0 = \left[\mathbf{I}_{N_i} \quad -\mathbf{Z}_{OL} \left(\begin{bmatrix} \mathbf{Z}_{InM_{N_i+1}} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{Rel} \end{bmatrix} + \mathbf{Z}_{LL} \right)^{-1} \right]$$



- $Z_{C'}$ is affected by the equivalent input impedances of the other receivers and the Antennae loads

$$\mathbf{Z}_C = \begin{bmatrix} \mathbf{Z}_{OO} & \mathbf{Z}_{OL} \\ \mathbf{Z}_{LO} & \mathbf{Z}_{LL} \end{bmatrix}$$

$$\mathbf{Z}_C' = \mathbf{Z}_{OO} - \mathbf{Z}_{OL} \left(\begin{bmatrix} \mathbf{Z}_{InM_{N_i+1}} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{Rel} \end{bmatrix} + \mathbf{Z}_{LL} \right)^{-1} \mathbf{Z}_{LO}$$

Receiver - Transfer Function

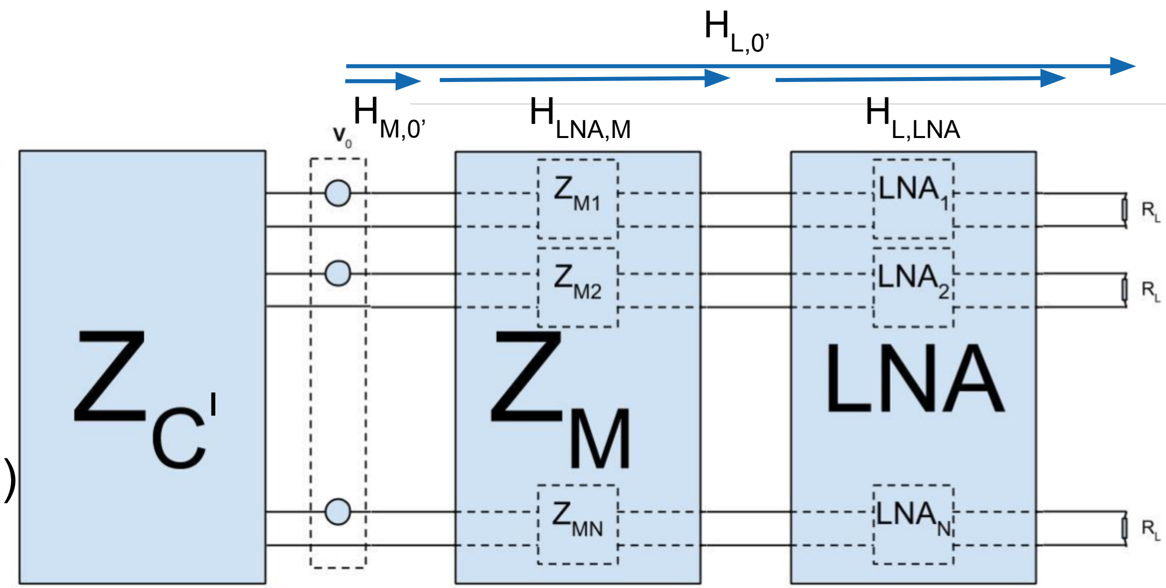
$$\mathbf{Z}_C' = \mathbf{Z}_{OO} - \mathbf{Z}_{OL}\left(\begin{bmatrix}\mathbf{Z}_{InM_{N_i+1}} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{Rel}\end{bmatrix} + \mathbf{Z}_{LL}\right)^{-1}\mathbf{Z}_{LO}$$

- Transfer the open circuit voltages to parallel input voltages

$$\mathbf{H}_{M,0'} = \mathbf{Z}_{inM_{N_i}} \cdot (\mathbf{Z}_{inM_{N_i}} + \mathbf{Z}_{C'})^{-1}$$

- The remaining transfer functions ($H_{L,LNA}$ and $H_{LNA,M}$) are independent of X_{Rel}.

$$\mathbf{H}_{L,0'} = \mathbf{H}_{L,LNA} \cdot \mathbf{H}_{LNA,M} \cdot \mathbf{H}_{M,0'}$$



Receiver - Interference

- To cancel the interference it is sufficient to look at the coupling transfer function (c.f. 6) and the spatial channel from the interferer

$$\mathbf{H}_0 = \begin{bmatrix} \mathbf{I}_{N_i} & -\mathbf{Z}_{OL} \left(\begin{bmatrix} \mathbf{Z}_{InM_{N_i+1}} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{Rel} \end{bmatrix} + \mathbf{Z}_{LL} \right)^{-1} \end{bmatrix}$$

$$\mathbf{H}_{sp} = \begin{bmatrix} \mathbf{H}_{1,Txi} \\ \mathbf{H}_{2,Txi} \\ \vdots \\ \mathbf{H}_{Rel,Txi} \end{bmatrix}, \text{and} \quad \mathbf{H}_0 \cdot \mathbf{H}_{sp} = \begin{bmatrix} \mathbf{I}_{N_i} & -\mathbf{Z}_{OL} \left(\begin{bmatrix} \mathbf{Z}_{InM_{N_i+1}} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{Rel} \end{bmatrix} + \mathbf{Z}_{LL} \right)^{-1} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{H}_{1,Txi} \\ \mathbf{H}_{2,Txi} \\ \mathbf{H}_{Rel,Txi} \end{bmatrix}$$

- As every later transfer function is applied as well to the signal part as to the interference part, an interference free connection is only achieved, if the following property holds

$$\mathbf{H}_{1,Tx_{Interf}} = \begin{bmatrix} \mathbf{Z}_{OL} \left(\begin{bmatrix} \mathbf{Z}_{InM_{N_i+1}} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{Rel} \end{bmatrix} + \mathbf{Z}_{LL} \right)^{-1} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{H}_{2,Tx_{Interf}} \\ \mathbf{H}_{Rel,Tx_{Interf}} \end{bmatrix}$$

Cost Functions

- User rate for user i:

$$r_i = \log\left(\det\left(\mathbf{K}_{S_i} + \mathbf{K}_{I_i} + \mathbf{K}_{n_i}\right)\right) - \log\left(\det\left(\mathbf{K}_{I_i} + \mathbf{K}_{n_i}\right)\right)$$

- Lp-Norm, in the following we look at the sum rate (p=1)

$$C(\mathbf{r}, p) = \|\mathbf{r}\|_p$$

- In the following, we try to maximize the cost function by gradient search

$$\underset{\mathbf{X}_{Rel}, \mathbf{Z}_M}{\text{maximize}} \; C(\mathbf{r}, p)$$

Behavior of the Function

We consider only two relays

We evaluate the sum rate

- against different load values
- at different input power

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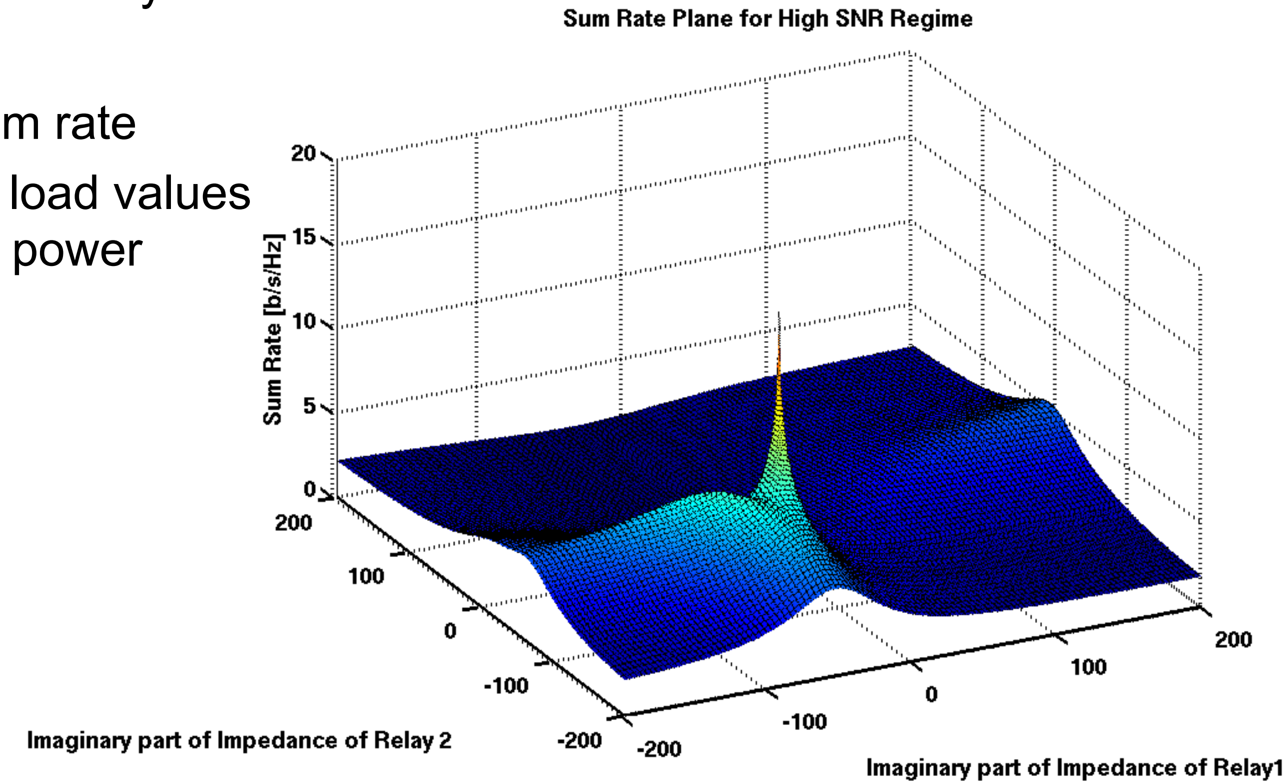
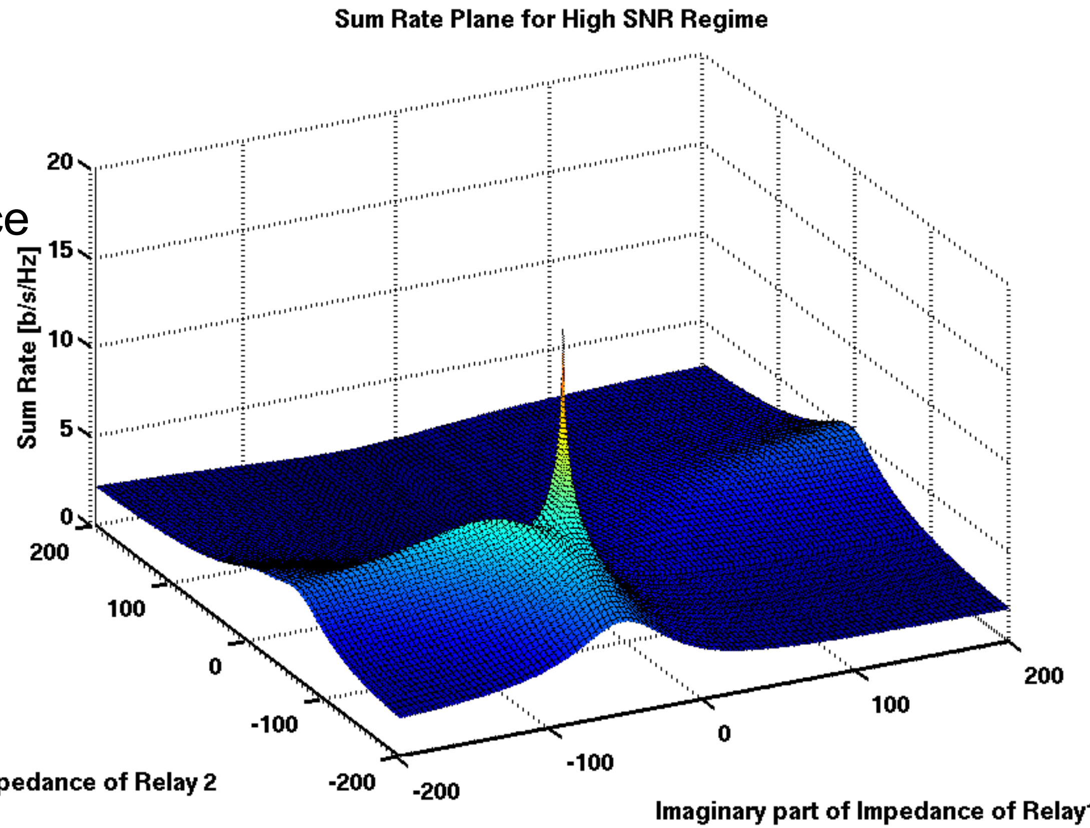


Behavior of the Function

Difficulties in finding the global maximum due to

- Non convex problem
- Optimal value shifts for different input power
- Large performance difference between local optimas



Gradient Search Optimization - Optimum Shifts

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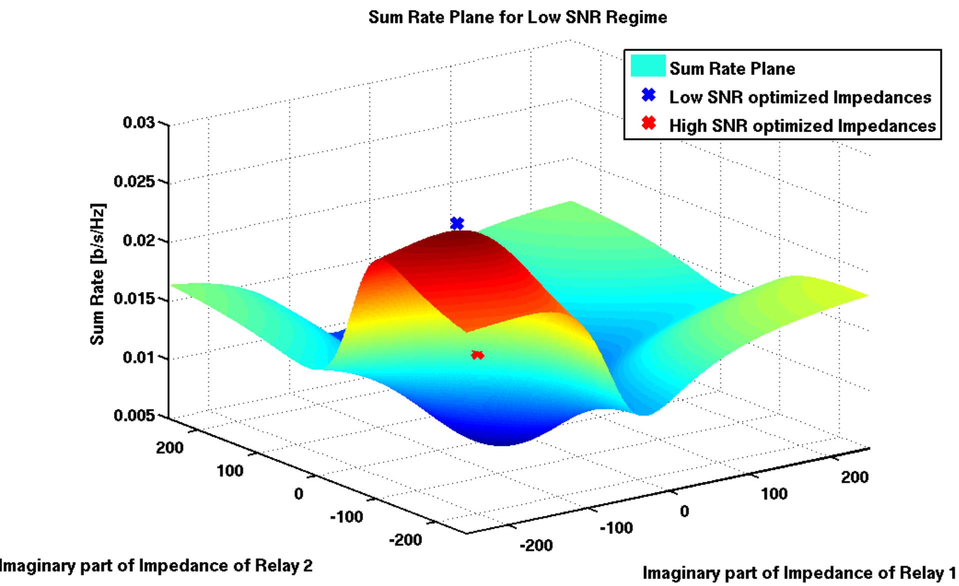

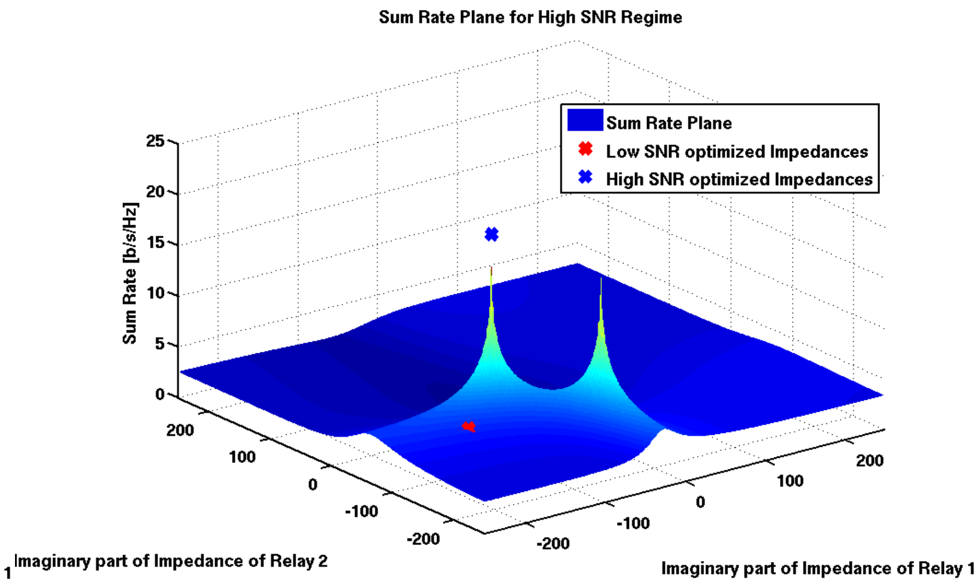

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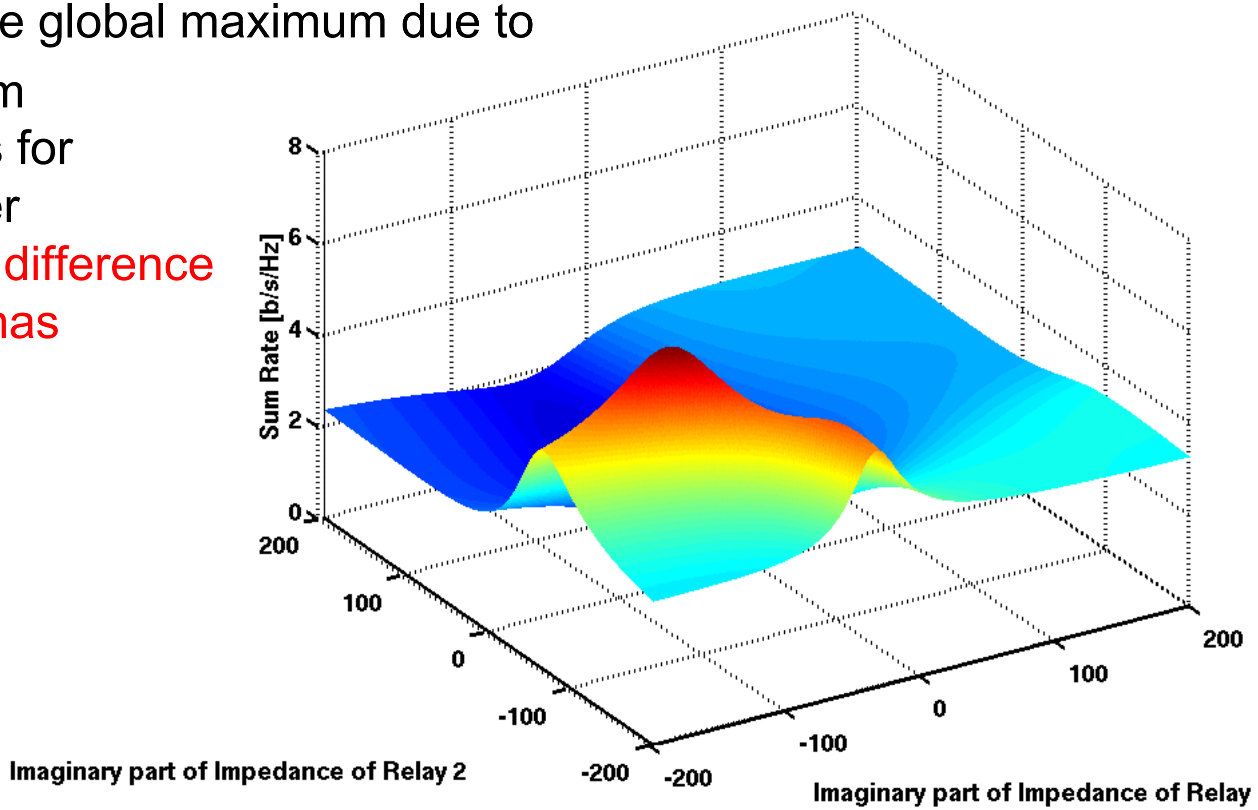
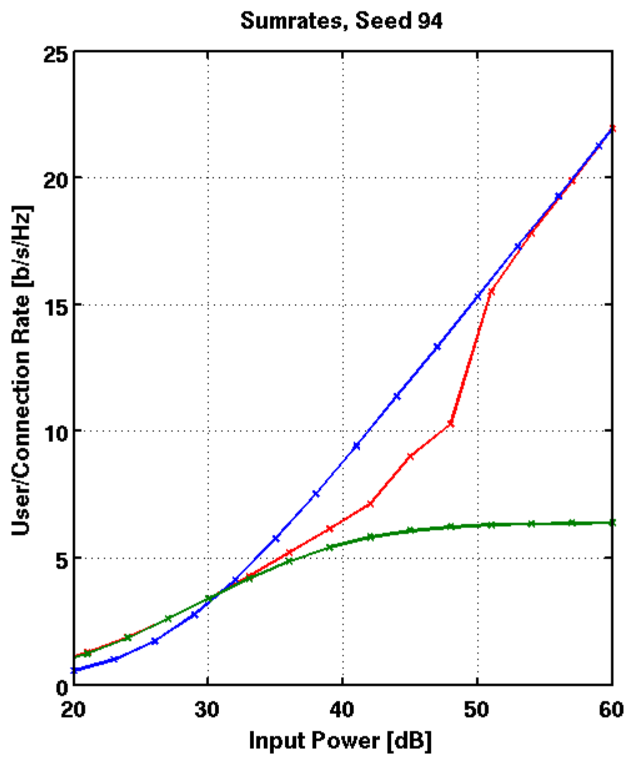
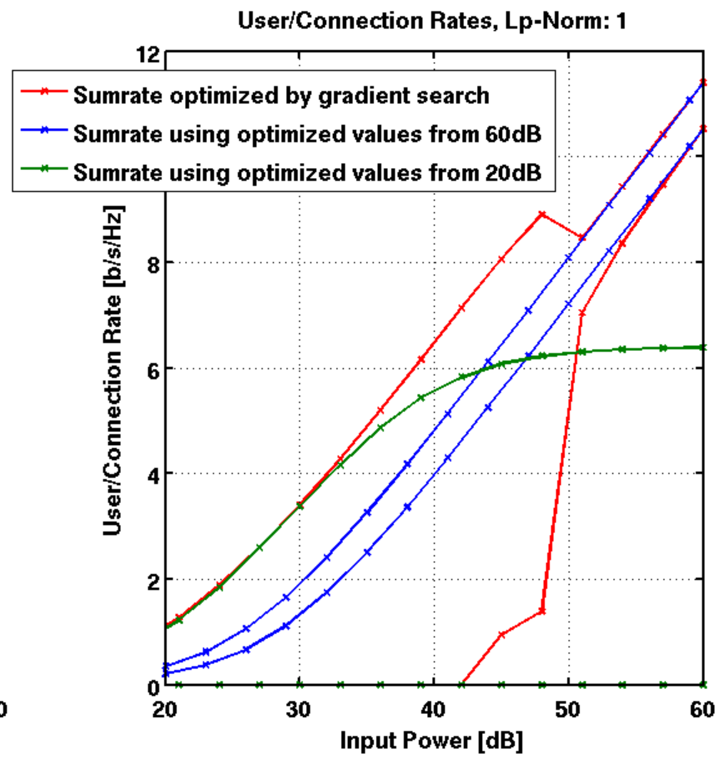


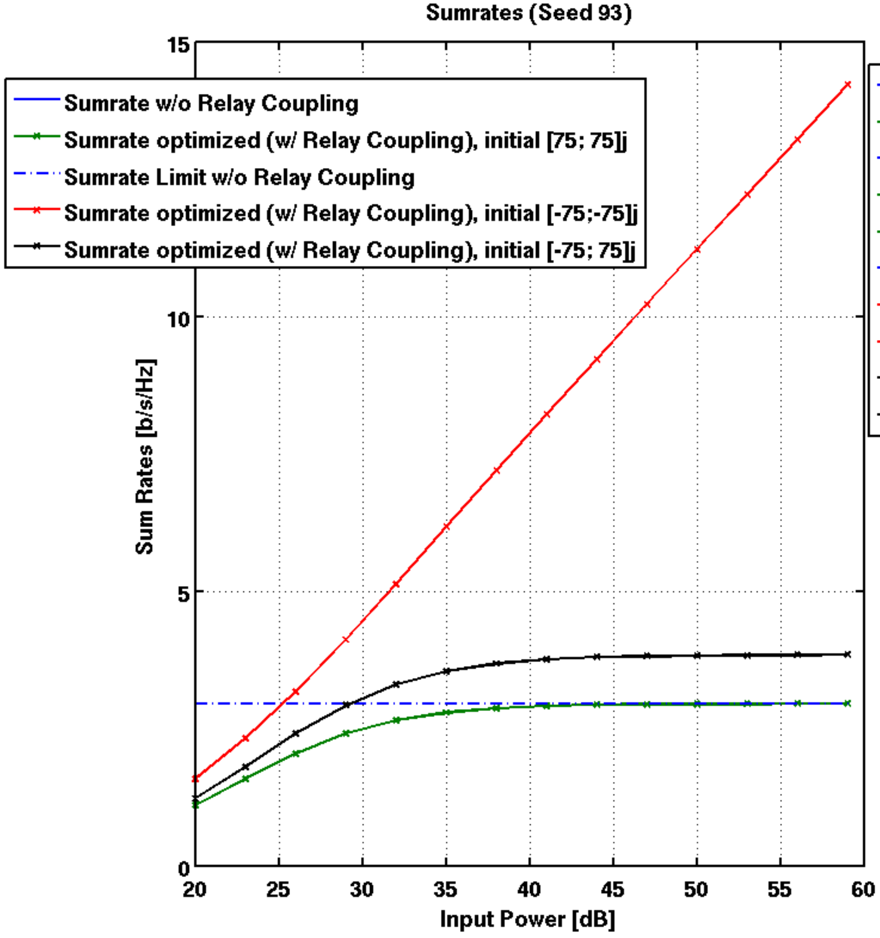
Gradient Search Optimization - Optimum Shifts

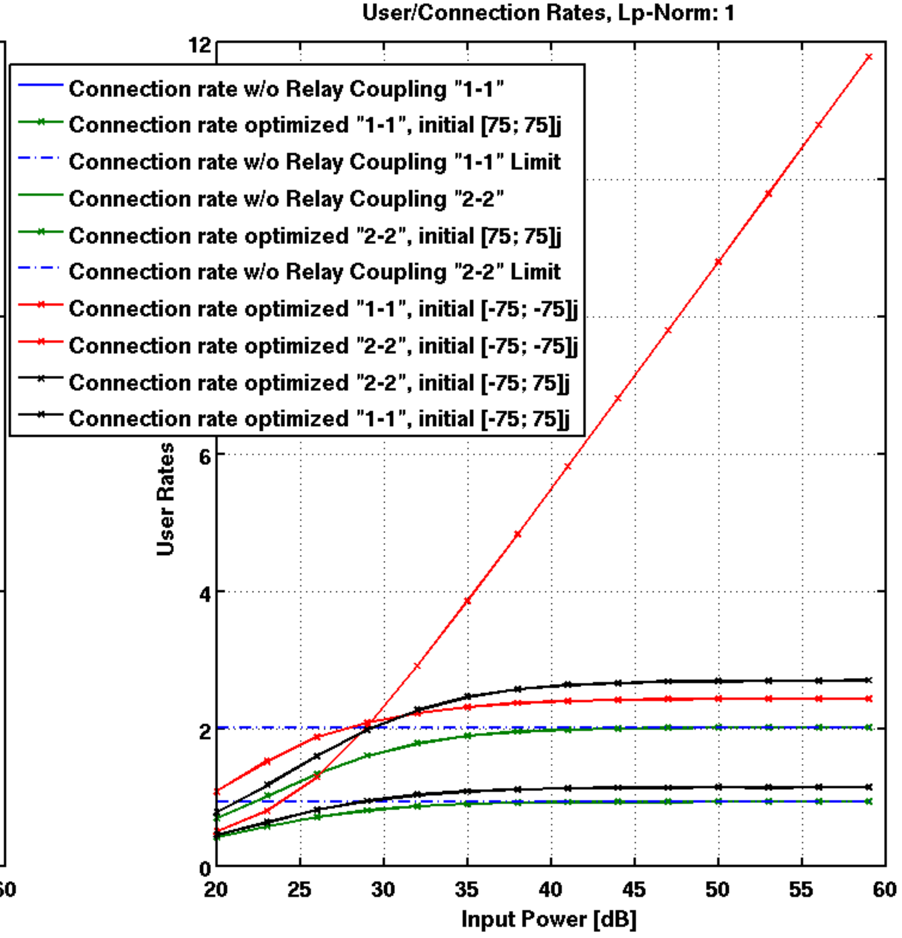
- Up to 30dB: optimizing only one of the connection pair and eliminating the other leads to a better performance.
- Over 30dB: gradient search runs into a local maximum - only for high SNR, the second connection is enabled.





Gradient Search Optimization - Local Optimas





Optimization

For the gradient search, the analytical gradient was derived

The gradient search is constrained, as the relays are pure imaginary and the submatrices of the matching network must be diagonal

An adaptive step size is used for faster convergence

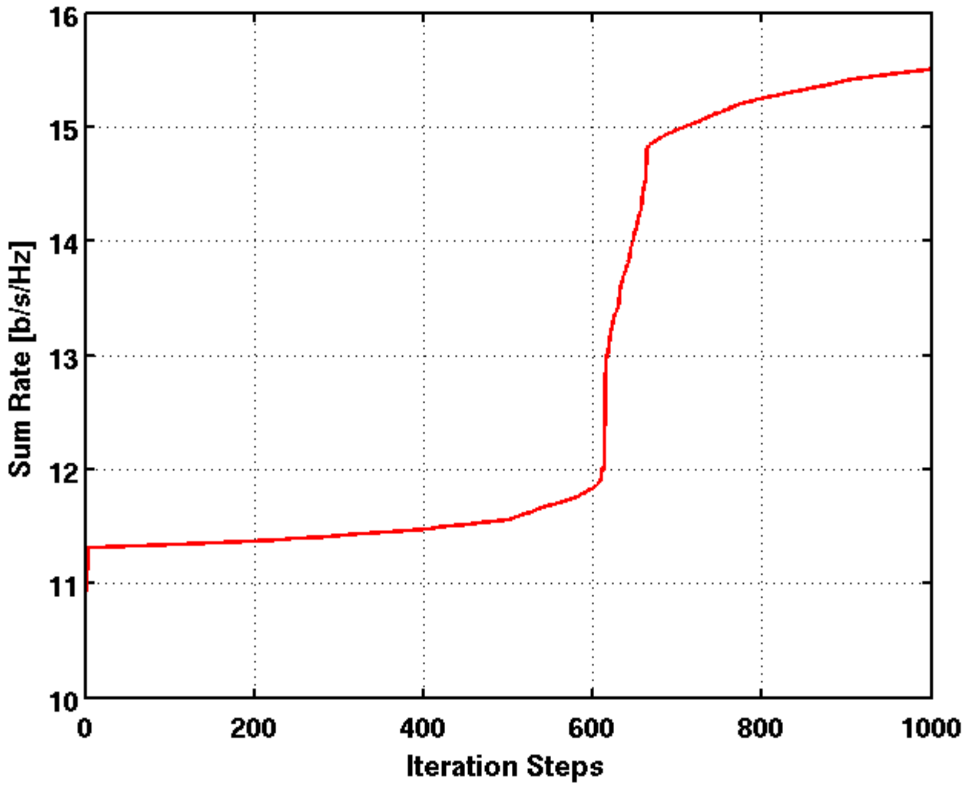
For correctness it was compared to

- the numerical gradient
- the existing method from Yahia
- the built-in function *fminunc*

Gradient Search Optimization - Convergence

Sum rate vs gradient iteration steps

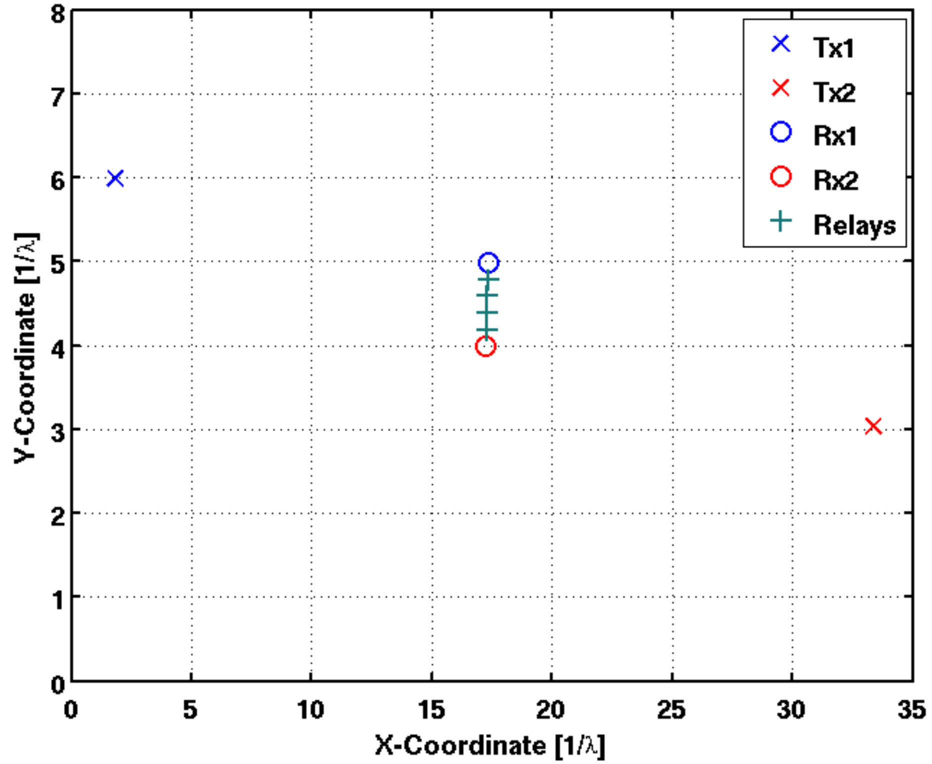
- Even after 500 iterations, the sum rate might not be converged



Simulation Settings

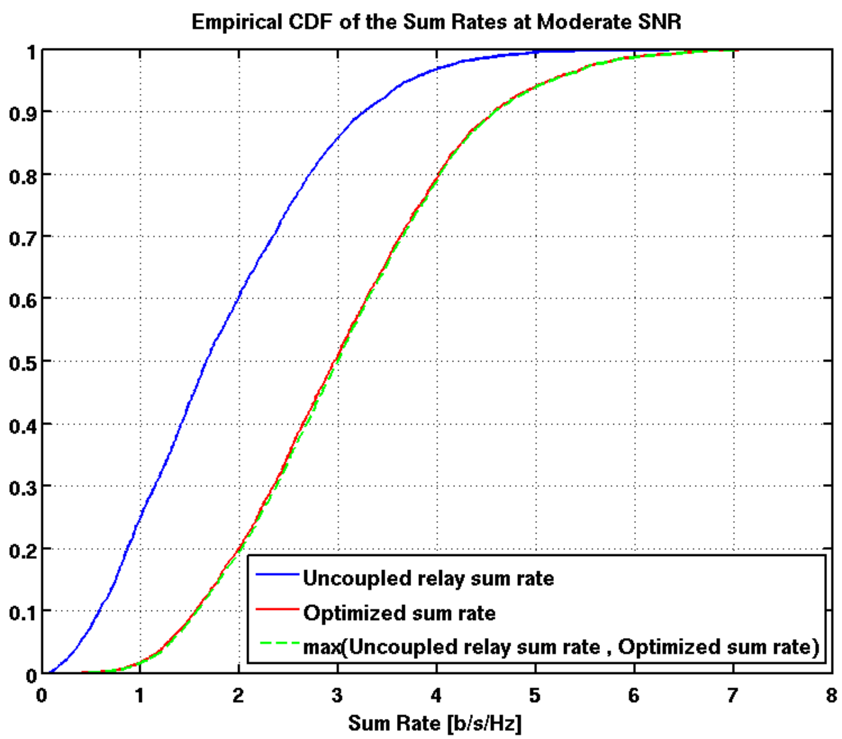
For the simulations, the following settings were used

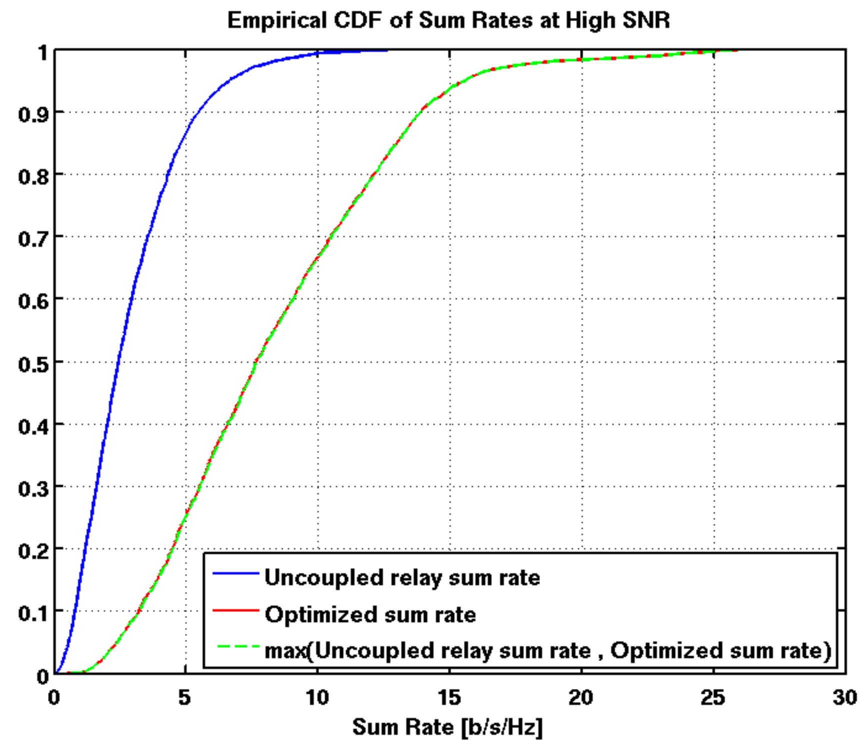
- No. of Relays: 4
- No. of Tx: 2
- No. of Tx antennae: 1
- No. of Rx: 2
- No. of Rx antennae: 1
- Lp-Norm: 1
- Gradient Iteration: 1500



Simulation Results

Empirical CDF-Plots at different SNRs for 4030 channel realizations





Simulation Results

Empirical CDF-Plots at different SNRs for XX channel realizations for only two relays

Outlook

Simulations with

- Larger number of transmit and receive antennae
- Different receiver structures (LMMSE)
- Larger number of relays
- Larger number of connection pairs
- Different precoding matrices at the transmitters

Gradient Search Optimization - Performance