Tutorial On: Unequal Error Protection in Multicarrier Mutliantenna Systems

Khaled Hassan - Werner Henkel

School of Engineering and Science

JACOBS UNIVERSITY

Summer Academy, 2007

Outline

Outline

Realizing UEP

- **UEP**: invokes the need for non-uniform error protection.
- **OFDM**: suitable for adapting individual subcarriers using different data rates, code rates, and powers
- **MIMO**: has high multiplexing gain and allows for channel layering.
- **UEP MIMO-OFDM**: devotes an arbitrary number of bits to different classes, eigenbeams, and subcarriers

Realizing UEP

- **UEP**: invokes the need for non-uniform error protection.
- **OFDM**: suitable for adapting individual subcarriers using different data rates, code rates, and powers
- **MIMO**: has high multiplexing gain and allows for channel layering.
- **UEP MIMO-OFDM**: devotes an arbitrary number of bits to different classes, eigenbeams, and subcarriers

Realizing UEP

- **UEP**: invokes the need for non-uniform error protection.
- **OFDM**: suitable for adapting individual subcarriers using different data rates, code rates, and powers
- **MIMO**: has high multiplexing gain and allows for channel layering.
- **UEP MIMO-OFDM**: devotes an arbitrary number of bits to different classes, eigenbeams, and subcarriers

Realizing UEP

- **UEP**: invokes the need for non-uniform error protection.
- **OFDM**: suitable for adapting individual subcarriers using different data rates, code rates, and powers
- **MIMO**: has high multiplexing gain and allows for channel layering.
- **UEP MIMO-OFDM**: devotes an arbitrary number of bits to different classes, eigenbeams, and subcarriers

Why UEP ?

- Source encoders of some applications deliver data of different importance.
- Matching the channel variations to enhance performance and spectral efficiency.
- The different error sensitivities of different communication devices, e.g., PDAs, laptops,···.

Why UEP ?

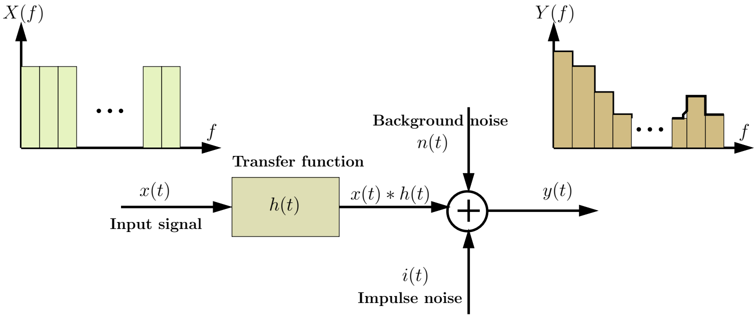
- Source encoders of some applications deliver data of different importance.
- Matching the channel variations to enhance performance and spectral efficiency.
- The different error sensitivities of different communication devices, e.g., PDAs, laptops,⋯.

Why UEP ?

- ◇ Source encoders of some applications deliver data of different importance.
- ◇ Matching the channel variations to enhance performance and spectral efficiency.
- ◇ The different error sensitivities of different communication devices, e.g., PDAs, laptops,$\cdots$.

Why Multicarrier ?

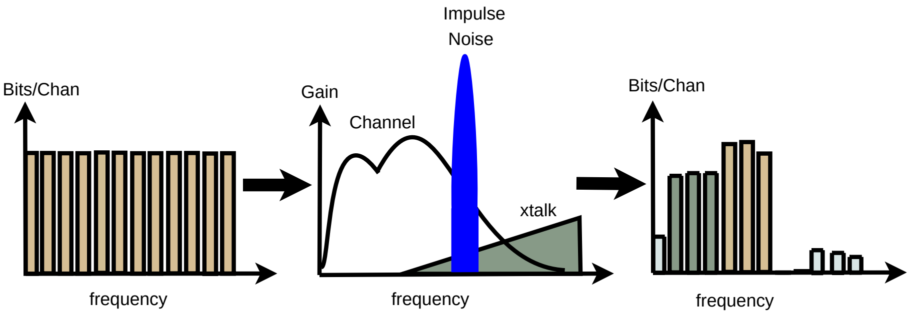
The available bandwidth is divided into N individual sub-channels



Due to its suitability for adapting individual subcarriers with different data rates, code rates, and power according channel conditions.

Why Multicarrier ?

The available bandwidth is divided into N individual sub-channels



Due to its suitability for adapting individual subcarriers with different data rates, code rates, and power according channel conditions.

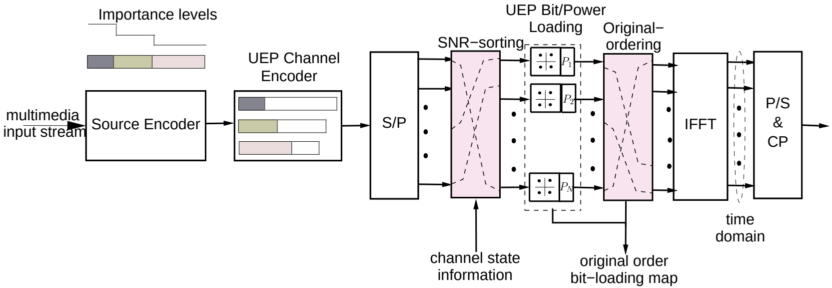
UEP Schemes in MCM

UEP coding Layer

Adapt coding scheme/rate (i.e., use puncturing or pruning)

UEP Physical Layer

Adapt bit/power loading and Physical Transport, e.g.: MIMO Channel



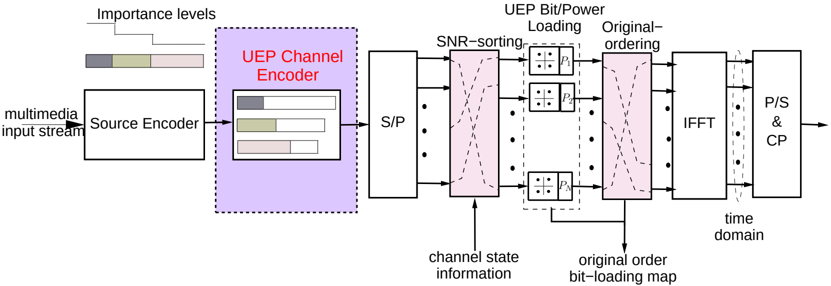
UEP Schemes in MCM

UEP coding Layer

Adapt coding scheme/rate (i.e., use puncturing or pruning)

UEP Physical Layer

Adapt bit/power loading and Physical Transport, e.g.: MIMO Channel



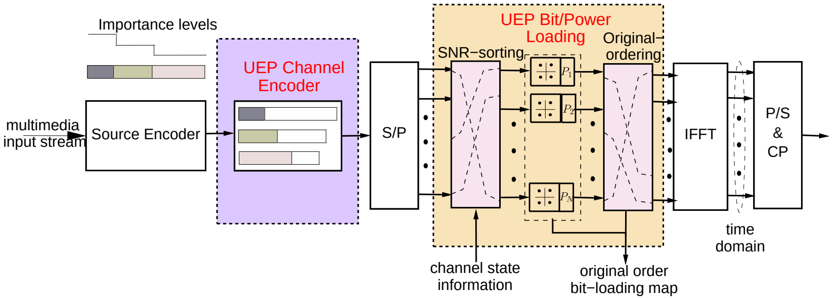
UEP Schemes in MCM

UEP coding Layer

Adapt coding scheme/rate (i.e., use puncturing or pruning)

UEP Physical Layer

Adapt bit/power loading and Physical Transport, e.g.: MIMO Channel



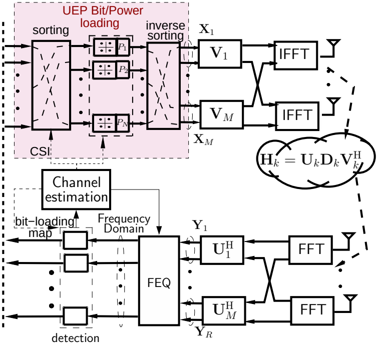
UEP Schemes in MCM

UEP coding Layer

Adapt coding scheme/rate (i.e., use puncturing or pruning)

UEP Physical Layer

Adapt bit/power loading and Physical Transport, e.g.: MIMO Channel



Outline

Principals

Modified Shannon's Capacity:

$$b_k = \log_2\left(1 + \frac{\mathrm{SNR}_k}{\gamma}\right)$$

Three conceptual problems:

- Bit-rate maximization problem (BRMP)
- Power minimization problem (PMP)
- Probability of error minimization problem(PEMP)

$$\max_{\hat{b} \in Z} \sum_{k=0}^{N-1} \hat{b}_k$$

subject to

$$\sum_{k=0}^{N-1} P_k(\hat{b}_k) < P_T$$

Principals

Modified Shannon's Capacity:

$$b_k = \log_2\left(1 + \frac{\text{SNR}_k}{\gamma}\right)$$

Three conceptual problems:

- Bit-rate maximization problem (BRMP)
- Power minimization problem (PMP)
- Probability of error minimization problem(PEMP)

$$\min_{\hat{b} \in Z} \sum_{k=0}^{N-1} P_k$$

subject to

$$\sum_{k=0}^{N-1} \hat{b}_k = B_T \quad \text{and} \quad \sum_{k=0}^{N-1} P_k \leq P_T$$

Principals

Modified Shannon's Capacity:

$$b_k = \log_2\left(1 + \frac{\mathrm{SNR}_k}{\gamma}\right)$$

Three conceptual problems:

- Bit-rate maximization problem (BRMP)
- Power minimization problem (PMP)
- Probability of error minimization problem(PEMP)

$$\min_{\hat{b}\in Z} \sum_{k=0}^{N-1} \mathscr{P}_{e,k}$$

subject to

$$\sum_{k=0}^{N-1} \hat{b}_k = B_T \quad \text{and} \quad \sum_{k=0}^{N-1} P_k \leq P_T$$

Bit-Loading Algorithms

Bit-loading solutions:

- Optimum: add bits to the locations of minimum incremental power, e.g.: Hughes-Hartogs and Campello
- Sub-optimum: based on Shannon capacity (**Chow et al.**) or probability of error minimization (Fischer-Huber and Yu-Willson)

Bit-Loading by Chow (BRMP):

$$b_k = \log_2\left(1 + \frac{\mathrm{SNR}_k}{\gamma}\right)$$

Quantization Error:

$$\begin{aligned} \hat{b}_k &= \lfloor b_k + 0.5 \rceil_0^{b_{\max}} \\ \Delta b_k &= b_k - \hat{b}_k \end{aligned}$$

Bit-Loading Algorithms

Bit-loading solutions:

- Optimum: add bits to the locations of minimum incremental power, e.g.: Hughes-Hartogs and Campello
- Sub-optimum: based on Shannon capacity (**Chow et al.**) or probability of error minimization (Fischer-Huber and Yu-Willson)

Bit-Loading by Chow (BRMP):

$$b_k = \log_2\left(1 + \frac{\mathrm{SNR}_k}{\gamma}\right)$$

Quantization Error:

$$\begin{aligned} \hat{b}_k &= \lfloor b_k + 0.5 \rfloor_0^{b_{\max}} \\ \Delta b_k &= b_k - \hat{b}_k \end{aligned}$$

Bit-Loading Algorithms

Bit-loading solutions:

- Optimum: add bits to the locations of minimum incremental power, e.g.: Hughes-Hartogs and Campello
- Sub-optimum: based on Shannon capacity (**Chow et al.**) or probability of error minimization (Fischer-Huber and Yu-Willson)

MIMO UEP Bit-Loading (BRMP):

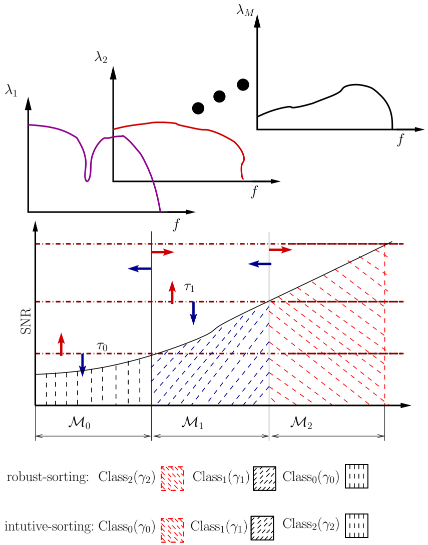
$$b_{k,l}^{(j)} = \log_2\left(1 + \frac{P_{k,l}^{(j)} \cdot \lambda_{k,l}^{(j)}}{\sigma^2 \cdot \gamma^{(j)}}\right)$$

Quantization Error:

$$\begin{aligned} \hat{b}_{k,l}^{(j)} &= \lfloor b_{k,l}^{(j)} + 0.5 \rfloor_0^{b_{\max}} \\ \Delta b_{k,l}^{(j)} &= b_{k,l}^{(j)} - \hat{b}_{k,l}^{(j)} \end{aligned}$$

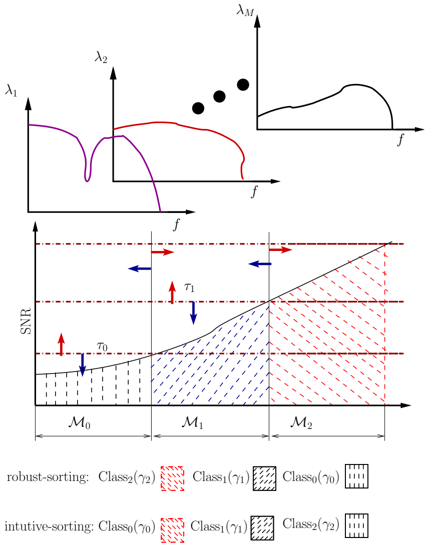
UEP Bit-Loading and SNR-Sorting Algorithms

- Compute $b_{k,l}^{(j)}$ using $\gamma^{(j)} = \gamma_0 - j \cdot \Delta\gamma$, then adjust $\mathscr{M}^{(j)}$ iteratively unit $\sum_{k,l} b_{k,l}^{(j)} = T^{(j)}$ or maximum iteration
- If B_T is not achieved, update γ_0 and recompute. If maximum iterations, add/subtract bits according to $\Delta b_k^{(j)}$
- The power is allocated according to SER. If the target SER is not fulfilled, reduce the total rate



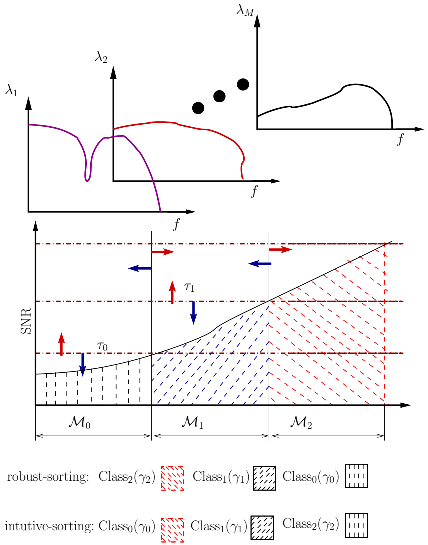
UEP Bit-Loading and SNR-Sorting Algorithms

- Compute $b_{k,l}^{(j)}$ using $\gamma^{(j)} = \gamma_0 - j \cdot \Delta\gamma$, then adjust $\mathscr{M}^{(j)}$ iteratively unit $\sum_{k,l} b_{k,l}^{(j)} = T^{(j)}$ or maximum iteration
- If B_T is not achieved, update γ_0 and recompute. If maximum iterations, add/subtract bits according to $\Delta b_k^{(j)}$
- The power is allocated according to SER. If the target SER is not fulfilled, reduce the total rate



UEP Bit-Loading and SNR-Sorting Algorithms

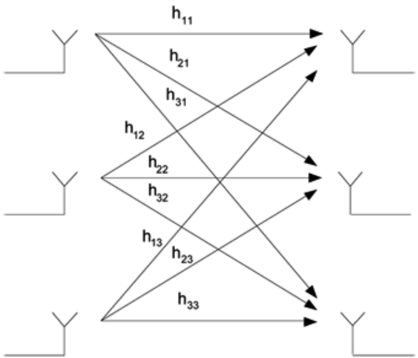
- Compute $b_{k,l}^{(j)}$ using $\gamma^{(j)} = \gamma_0 - j \cdot \Delta\gamma$, then adjust $\mathscr{M}^{(j)}$ iteratively unit $\sum_{k,l} b_{k,l}^{(j)} = T^{(j)}$ or maximum iteration
- If B_T is not achieved, update γ_0 and recompute. If maximum iterations, add/subtract bits according to $\Delta b_k^{(j)}$
- The power is allocated according to SER. If the target SER is not fulfilled, reduce the total rate



Outline

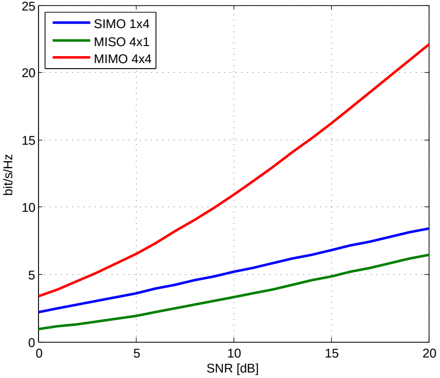
Potential of MIMO wireless links:

- substantial improvement in QoS/throughput
- Effectively exploit multipath
- Scalability and adaptation



Potential of MIMO wireless links:

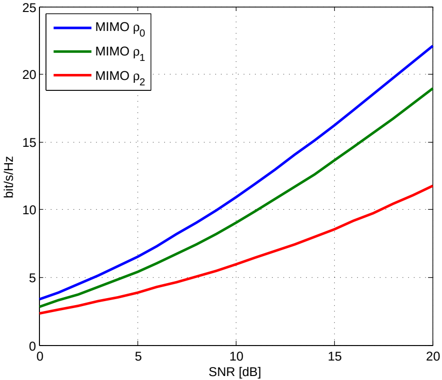
- substantial improvement in QoS/throughput
- Effectively exploit multipath
- Scalability and adaptation



$$C_E = E\left[\det\left(\log_2\left\{I_{M_R} + \frac{\rho}{N_T}\mathbf{HH}^H\right\}\right]\right)$$
bits/sec/Hz

Potential of MIMO wireless links:

- substantial improvement in QoS/throughput
- Effectively exploit multipath
- Scalability and adaptation

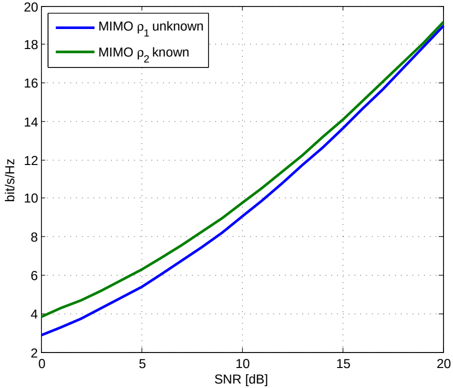


$$C_E = E\left[\det\left(\log_2\left\{I_{M_R} + \mathbf{HQH}^H\right\}\right]\right)$$
bits/sec/Hz

where $Q = E[x * x^H]$

Potential of MIMO wireless links:

- substantial improvement in QoS/throughput
- Effectively exploit multipath
- Scalability and adaptation



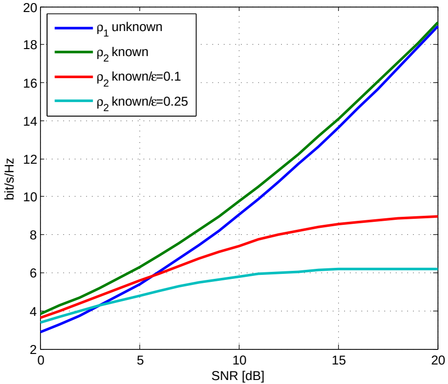
$C_E = \sum_{i=1}^{M} \log_2 \left(1 + \frac{\rho_{\mathrm{WF}}}{N_T} \lambda_i\right)$ bits/sec/Hz

where $\mathrm{tr}(\mathbf{Q}) \leq \rho_{\mathrm{WF}}$

$\rho_{WF} = \sum_{i=1}^{M} \left(\mu - \lambda_i^{-1}\right)^{+}$

Potential of MIMO wireless links:

- substantial improvement in QoS/throughput
- Effectively exploit multipath
- Scalability and adaptation



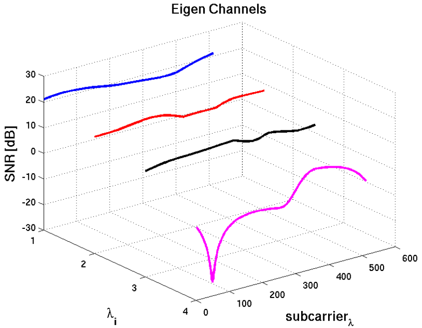
$$C_E = \sum_{i=1}^{M} \log_2 \left(1 + \frac{\rho_{\mathrm{WF}}}{N_T(1+\sigma_E \overline{P})} \lambda_i\right)$$
bits/sec/Hz

where $\mathrm{tr}(\mathbf{Q}) \leq \rho_{\mathrm{WF}}$

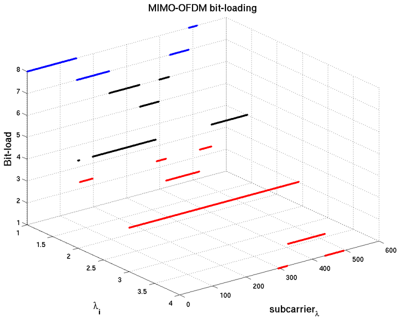
$$\rho_{WF} = \sum_{i=1}^{M} \left(\mu - \lambda_i^{-1}\right)^{+}$$

Eigen Channels Representation

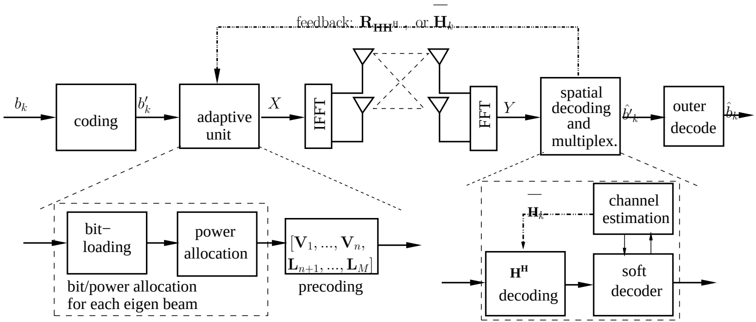
Eigen channels (modes)



Bit-loading for eigen channels



Channel side information feedback



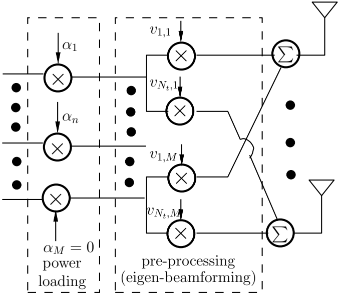
CSI feedback:

- Channel mean: $\hat{\mathbf{H}} = \mathbf{H} - \varepsilon_e$, $\overline{\mathbf{U}}\mathbf{D}^{\frac{1}{2}}\overline{\mathbf{V}^{\mathbf{H}}}$
- Channel corelation: $R_{\hat{\mathbf{H}}^H\hat{\mathbf{H}}} = E\{\hat{H}\hat{H}^*\} = \overline{\mathbf{V}}\mathbf{D}\overline{\mathbf{V}^{\mathbf{H}}}$

CSI uncertainty:

- Channel estimation error
- Quantization error
- errors included by the feedback channel
- Variation during channel feedback

Beamforming Scheme



The rank = M & $0 < n \leq M - 1$

$\therefore \overline{\mathbf{V}} = [\overline{\mathbf{V}}_1 \overline{\mathbf{V}}_2]$,

where $\overline{\mathbf{V}}_1 = [v_1, ..., v_n]$ and

$\overline{\mathbf{V}}_2 = [0_{n+1}, .., 0_M]$.

Eigen beamforming selection

- full-beamforming (full-BF) at $n = M$
- suppress weaker eigenbeams
- shorter BF length due to antenna correlation or CSI errors
  - Direct BF: $\overline{V}_1$ are adjacent columns.
  - Selecte BF: $\overline{V}_1$ are selected to minimize interference

Beamforming Analysis

CSI error: $\hat{\mathbf{H}}_k = \overline{\mathbf{H}}_k + \Xi_k$
where $\Xi_k \sim \mathcal{CN}(0, \sigma_{\Xi}^2)$
the received vector:

$$\begin{aligned} \mathbf{Y}_k &= \hat{\mathbf{H}}_k \overline{\mathbf{V}}_k \mathbf{P}^{1/2} \mathbf{X}_k + n_k \\ &= \overbrace{\hat{\mathbf{U}}_k \hat{\mathbf{D}}_k \hat{\mathbf{V}}_k^* \overline{\mathbf{V}}_k \mathbf{P}^{1/2}}^{\mathbf{T}_k} \mathbf{X}_k + \eta_k \ , \end{aligned}$$

ZF-MRC detection:

$$\mathbf{W} = \{\mathbf{T}^*\mathbf{T}\}^{-1}\mathbf{T}^{\mathrm{H}}$$

$$\hat{\mathbf{x}} = \mathbf{W}\mathbf{y}$$

MMSE-MRC detection:

$$\mathbf{W} = \{\mathbf{T}^*\mathbf{T} + \sigma_{\mathrm{N}}^2\mathbf{I}\}^{-1}\mathbf{T}^{\mathrm{H}}$$

$$\hat{\mathbf{x}} = \mathbf{W}\mathbf{y}$$

Beamforming Analysis

CSI error: $\hat{\mathbf{H}}_k = \overline{\mathbf{H}}_k + \Xi_k$
where $\Xi_k \sim \mathscr{C}\mathscr{N}(0, \sigma_{\Xi}^2)$
the received vector:

$$\begin{aligned}\mathbf{Y}_k &= \hat{\mathbf{H}}_k \overline{\mathbf{V}}_k \mathbf{P}^{1/2} \mathbf{X}_k + n_k \\ &= \overbrace{\hat{\mathbf{U}}_k \hat{\mathbf{D}}_k \hat{\mathbf{V}}_k^* \overline{\mathbf{V}}_k \mathbf{P}^{1/2}}^{\mathbf{T}_k} \mathbf{X}_k + \eta_k ,\end{aligned}$$

ZF-MRC detection:

$$\mathbf{W} = \{\mathbf{T}^*\mathbf{T}\}^{-\mathbf{1}}\mathbf{T}^{\mathrm{H}}$$

$$\hat{\mathbf{x}} = \mathbf{W}\mathbf{y}$$

MMSE-MRC detection:

$$\mathbf{W} = \{\mathbf{T}^*\mathbf{T} + \sigma_{\mathbf{N}}^{\mathbf{2}}\mathbf{I}\}^{-\mathbf{1}}\mathbf{T}^{\mathrm{H}}$$

$$\hat{\mathbf{x}} = \mathbf{W}\mathbf{y}$$

Outline

1. Motivations
   - Motivations for UEP, OFDM, and MIMO
2. UEP: Bit-Loading
   - Previous Work
   - Proposed Algorithm
3. MIMO-OFDM and Eigen Beamforming
   - MIMO Principals
   - Beamforming in MIMO-OFDM
4. Simulation Results
   - Simulation Parameters
   - UEP Adaptive MIMO-OFDM Results
5. Conclusions

Channel Model and System Parameters:

- **Channel**: MIMO Rayleigh fading channel with different correlation models
- **MIMO Parameters**: 4×4 MIMO-OFDM system with 512 subcarriers for each beam
- **Bit-loading**: the maximum allowed bits per subchannel is 8
- **UEP Application**: 3 classes, $\Delta\gamma^{(j)} = 3$ dB, $T^{(j)} = 1024$ bits

Channel Model and System Parameters:

- **Channel**: MIMO Rayleigh fading channel with different correlation models
- **MIMO Parameters**: 4×4 MIMO-OFDM system with 512 subcarriers for each beam
- **Bit-loading**: the maximum allowed bits per subchannel is 8
- **UEP Application**: 3 classes, $\Delta\gamma^{(j)} = 3$ dB, $T^{(j)} = 1024$ bits

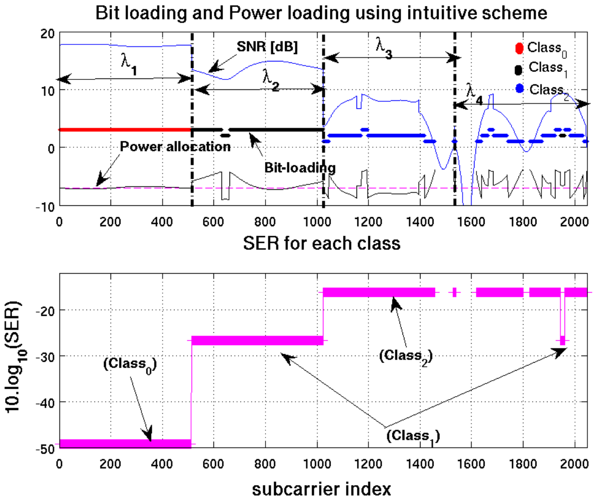
Channel Model and System Parameters:

- **Channel**: MIMO Rayleigh fading channel with different correlation models
- **MIMO Parameters**: 4×4 MIMO-OFDM system with 512 subcarriers for each beam
- **Bit-loading**: the maximum allowed bits per subchannel is 8
- **UEP Application**: 3 classes, $\Delta\gamma^{(j)} = 3$ dB, $T^{(j)} = 1024$ bits

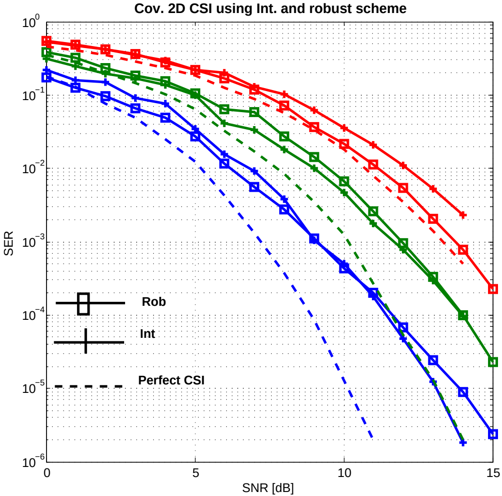
Channel Model and System Parameters:

- **Channel**: MIMO Rayleigh fading channel with different correlation models
- **MIMO Parameters**: 4×4 MIMO-OFDM system with 512 subcarriers for each beam
- **Bit-loading**: the maximum allowed bits per subchannel is 8
- **UEP Application**: 3 classes, $\Delta\gamma^{(j)} = 3$ dB, $T^{(j)} = 1024$ bits

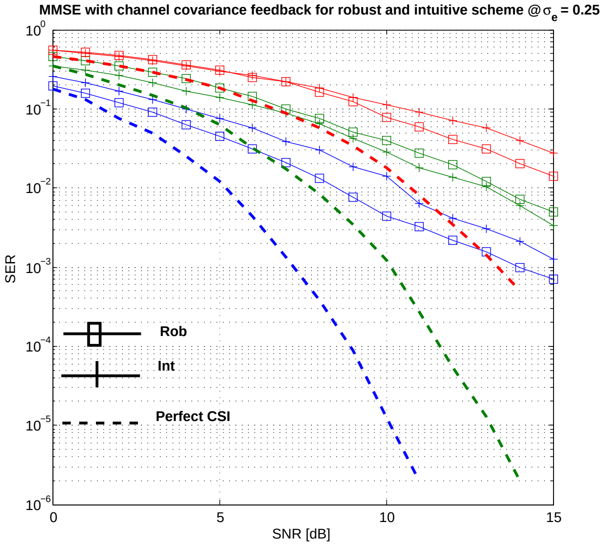
UEP Bit Power Allocation for perfect CSI:



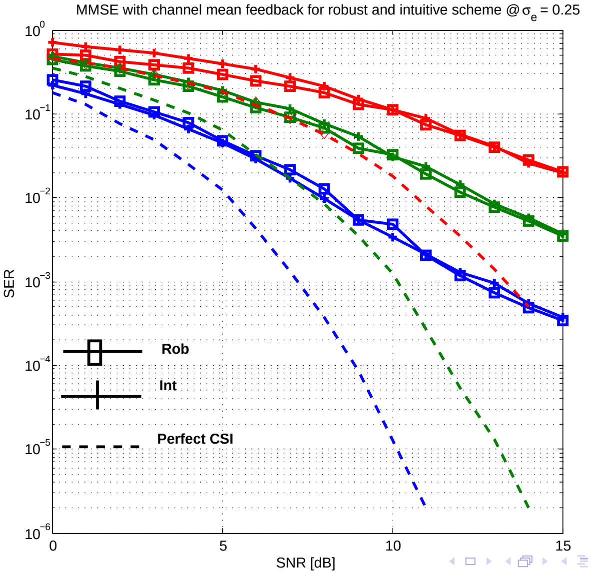
perfect and imperfect CSI (2D results @ε_e =0.1)



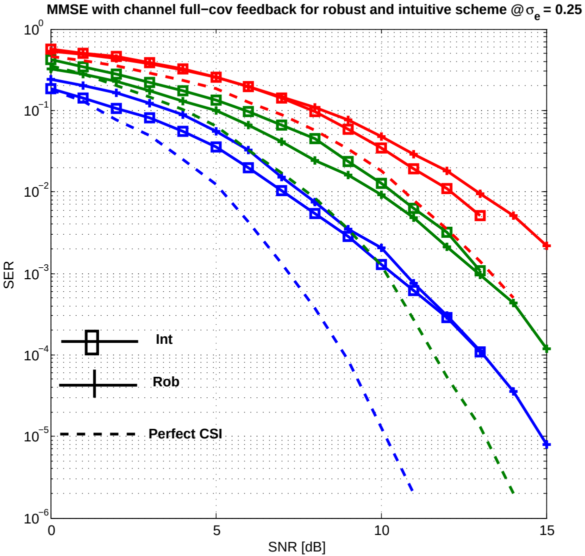
Different CSI errors (2D results @ε_e =0.25):



Different Beamforming Techniques (full beamforming):



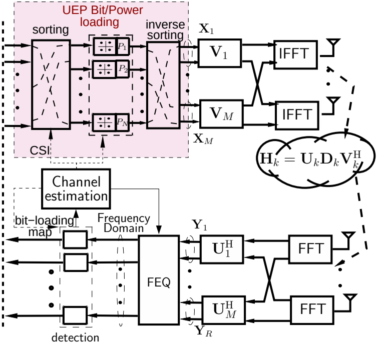
Different Beamforming Techniques (full beamforming):



Outline

Conclusions

- We described an UEP bit-allocation scheme for MIMO-OFDM
- Exploit channel layering using SVD, thereby realize UEP
- Allows for arbitrary margins, error probabilities, and bit-rates
- Selected beamforming is a practical solution for suppressing CSI errors.

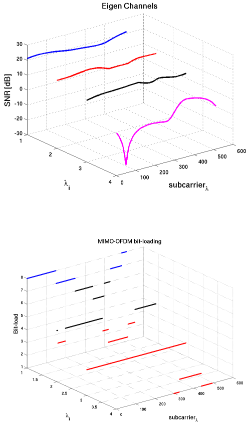


Ongoing Research:

We are studying the combination of spatial equalizers, IC, beamforming, and STBC to minimize the CSI errors effect.

Conclusions

- We described an UEP bit-allocation scheme for MIMO-OFDM
- Exploit channel layering using SVD, thereby realize UEP
- Allows for arbitrary margins, error probabilities, and bit-rates
- Selected beamforming is a practical solution for suppressing CSI errors.

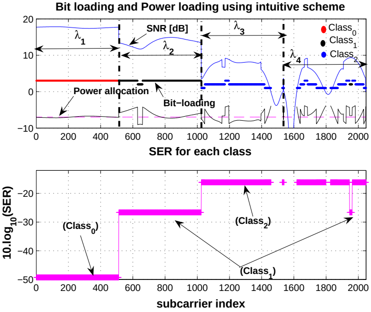


Ongoing Research:

We are studying the combination of spatial equalizers, IC, beamforming, and STBC to minimize the CSI errors effect.

Conclusions

- We described an UEP bit-allocation scheme for MIMO-OFDM
- Exploit channel layering using SVD, thereby realize UEP
- Allows for arbitrary margins, error probabilities, and bit-rates
- Selected beamforming is a practical solution for suppressing CSI errors.

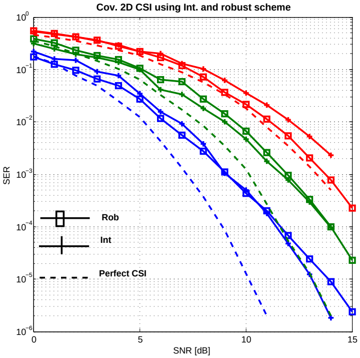


Ongoing Research:

We are studying the combination of spatial equalizers, IC, beamforming, and STBC to minimize the CSI errors effect.

Conclusions

- We described an UEP bit-allocation scheme for MIMO-OFDM
- Exploit channel layering using SVD, thereby realize UEP
- Allows for arbitrary margins, error probabilities, and bit-rates
- Selected beamforming is a practical solution for suppressing CSI errors.



Ongoing Research:

We are studying the combination of spatial equalizers, IC, beamforming, and STBC to minimize the CSI errors effect.

Conclusions

- We described an UEP bit-allocation scheme for MIMO-OFDM
- Exploit channel layering using SVD, thereby realize UEP
- Allows for arbitrary margins, error probabilities, and bit-rates
- Selected beamforming is a practical solution for suppressing CSI errors.

Ongoing Research:

We are studying the combination of spatial equalizers, IC, beamforming, and STBC to minimize the CSI errors effect.

Questions!

CSI Error Effect