Ad Hoc CoMP in the Uplink of Backhaul Constrained Cellular Systems

33. Treffen der VDE/ITG-Fachgruppe 5.2.4

NEC, Heidelberg

July, 08 2010

Michael Grieger

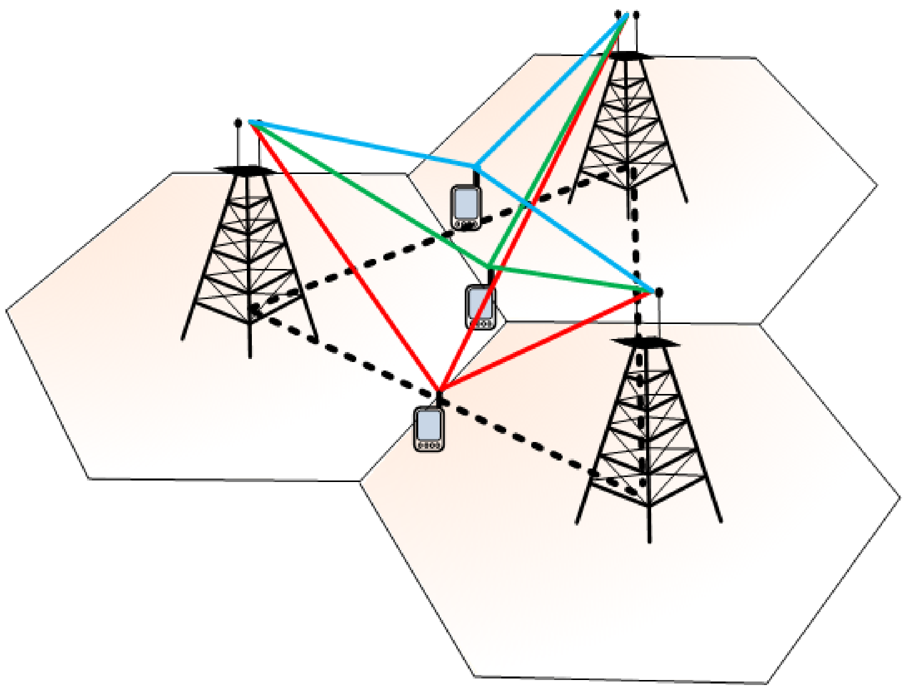
Contents

Contents

- Introduction
- Ad Hoc CoMP with Adaptive Compression
- Ad Hoc CoMP with Progressive Compression
- Summary & Future Work

Introduction

- Consider a **reuse 1** system
- High performance when users located in vicinity of assigned base stations
- Interference problem when users are located at cell edges
- **In general:** Cellular communications systems with independent base stations are interference limited



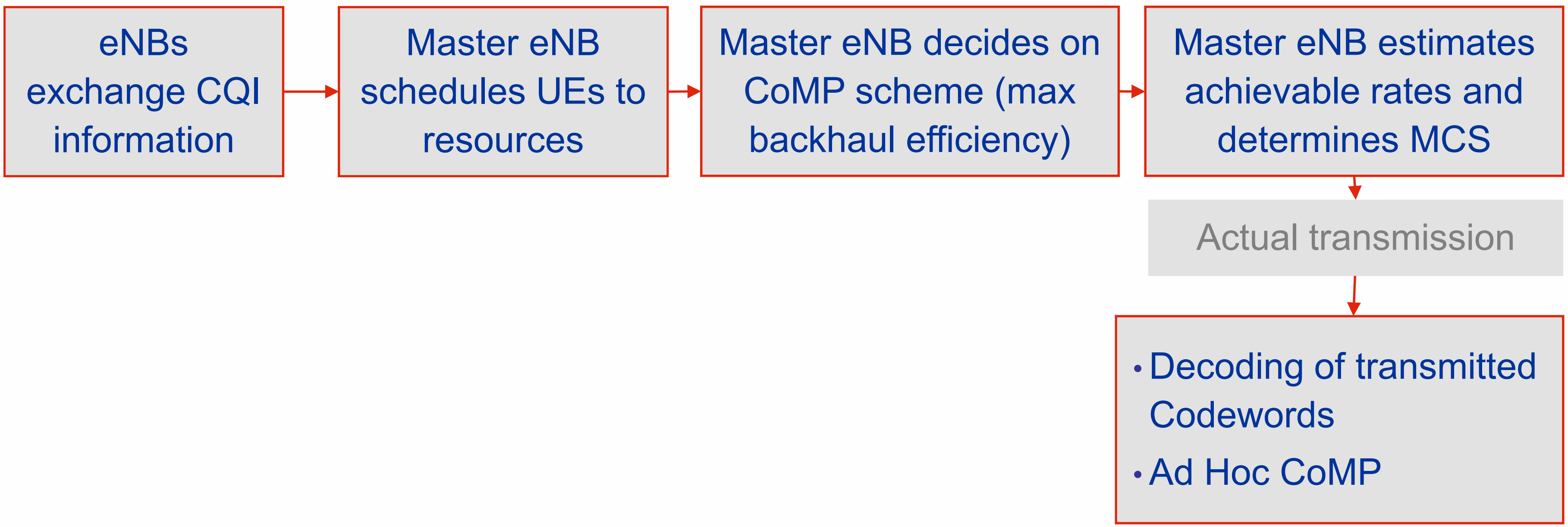
⇨ Base station cooperation to

- Jointly transmit/detect
- Mitigate interference
- Increase spectral efficiency

We are interested in the uplink of a system with limited backhaul capacity.

Introduction

- Scheduling and ad-hoc CoMP processs



- **Problem**

  Decision on achievable rates at the scheduler is based on imperfect information regarding e.g. channel state and noise variance.

- **Possible solution**

  Take changed channel state and decoding success into account to make ad hoc decision on CoMP schemes after transmission.

Contents

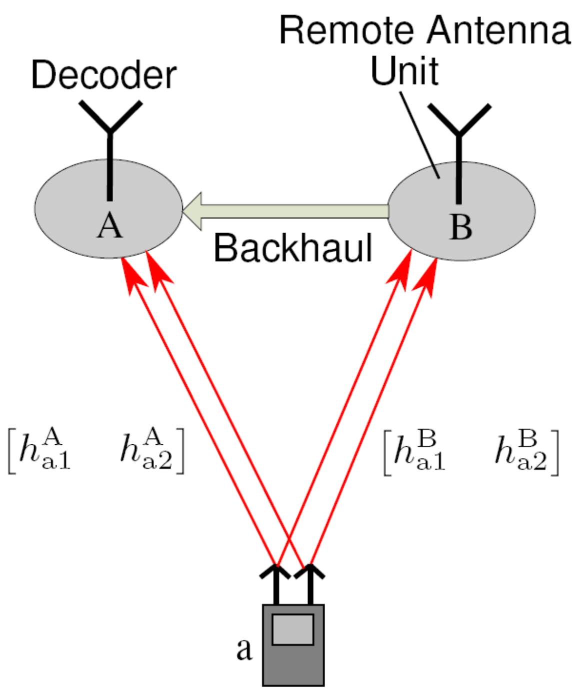
Ad Hoc CoMP with Adaptive Compression

System and Transmission Model

TECHNISCHE UNIVERSITÄT DRESDEN

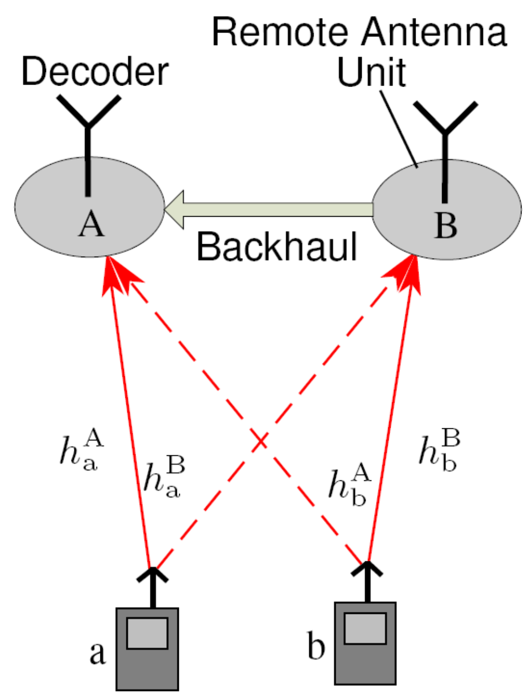
vodafone chair

System with one MT



$$\begin{bmatrix} y_A \\ y_B \end{bmatrix} = \underbrace{\begin{bmatrix} h_{a_1}^{A}[n] & h_{a_2}^{A}[n] \\ h_{a_1}^{B}[n] & h_{a_2}^{B}[n] \end{bmatrix}}_{\mathbf{H}[n]} \mathbf{x} + \underbrace{\begin{bmatrix} v_A \\ v_B \end{bmatrix}}_{\mathbf{v}} + \begin{bmatrix} 0 \\ q_B(c) \end{bmatrix}$$

System with two MTs



$$\begin{bmatrix} y_A \\ y_B \end{bmatrix} = \underbrace{\begin{bmatrix} h_{a}^{A}[n] & h_{b}^{A}[n] \\ h_{a}^{B}[n] & h_{b}^{B}[n] \end{bmatrix}}_{\mathbf{H}[n]} \mathbf{x} + \underbrace{\begin{bmatrix} v_A \\ v_B \end{bmatrix}}_{\mathbf{v}} + \begin{bmatrix} 0 \\ q_B(c) \end{bmatrix}$$

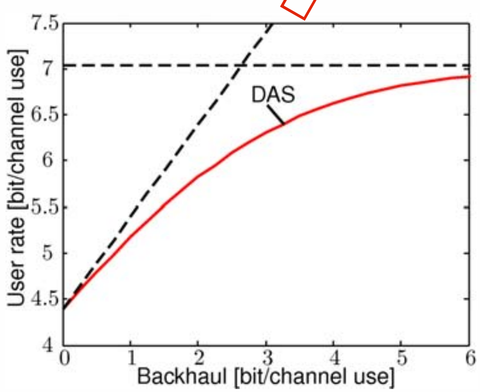
Ad Hoc CoMP with Adaptive Compression
Problem Statement

TECHNISCHE UNIVERSITÄT DRESDEN

vodafone chair

- Scheduling and ad-hoc decoding process for distributed antenna systems:

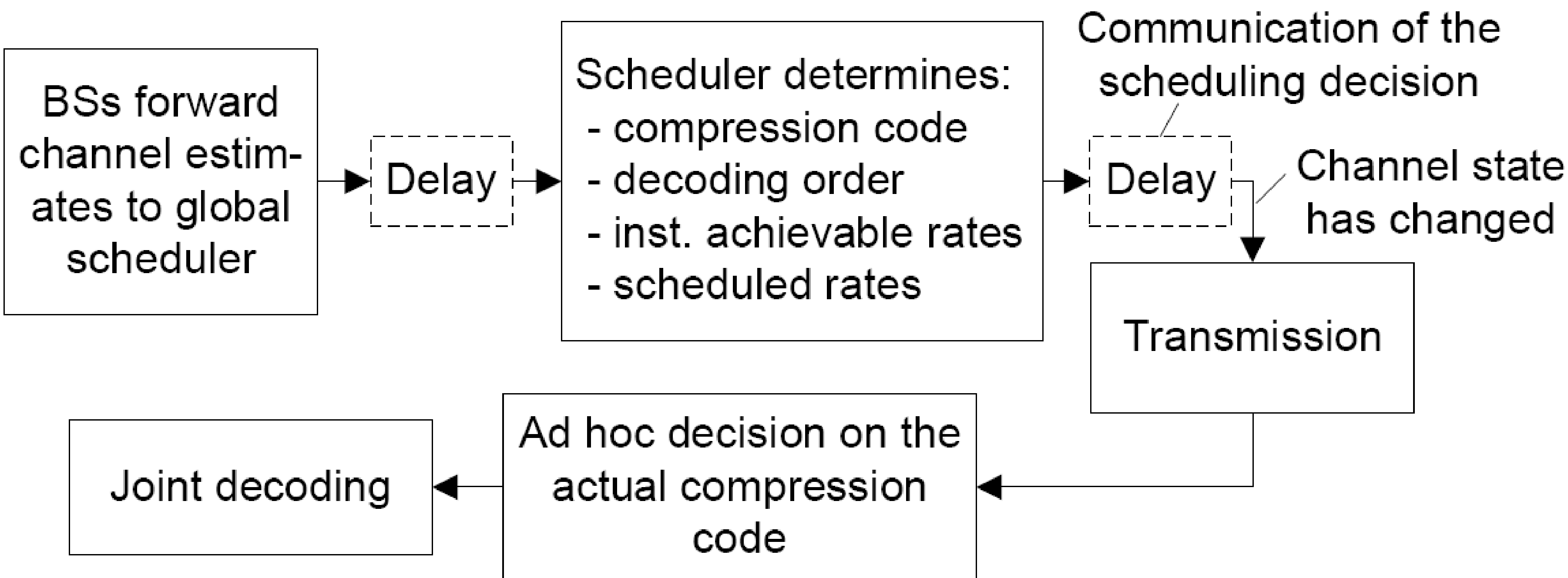
eNBs exchange CQI information → Master eNB schedules UEs to resources → Master eNB decides on quantization rate and decoding orders → Master eNB estimates achievable rates and determines MCS → Actual transmission → Exchange of quantized received signal to master eNB → Joint decoding of transmitted codewords



- **Problem**
  - Decision on quantization rate is based on imperfect channel information because of scheduling delay
- **Possible Solution**
  - Exploit the fact that we have better channel knowledge after transmission

Ad Hoc CoMP with Adaptive Compression

Proposed Algorithm



We define three rates

$r_m[n, c]$	Rate of MT k	n	number of transmission block
$r_{s,k}[n]$	Scheduled Rate of MT k	c	backhaul rate
$r_{\text{fix},k}[n] = r_k[n, c_{\text{fix}}]$	Rate of MT k for $c = c_{\text{fix}}$		
$r_{\text{adapt},k}[n] = r_k[n, c_{\text{adapt}}]$	Rate of MT k for $c = c_{\text{adapt}}$		

What is the gain of an adaptive decision on the backhaul rate after transmission ?

At the scheduler

We assume that

- $r_{\mathrm{s},k}[n]$ is only a function of the channel state that was observed n_{d} symbols earlier
- always the same backhaul rate c_{fix} is used at the scheduler
- a backoff-factor Γ is used to trade-off peak-rate and outage probability

The scheduled rate of MT k thus is given by

$$r_{\mathrm{s},k}[n, c_{\mathrm{fix}}, \Gamma] = (1 - \Gamma) r_{\mathrm{fix},k}(n - n_{\mathrm{d}}), \ 0 \leq \Gamma \leq 1$$

At the receiver, we compare two different schemes

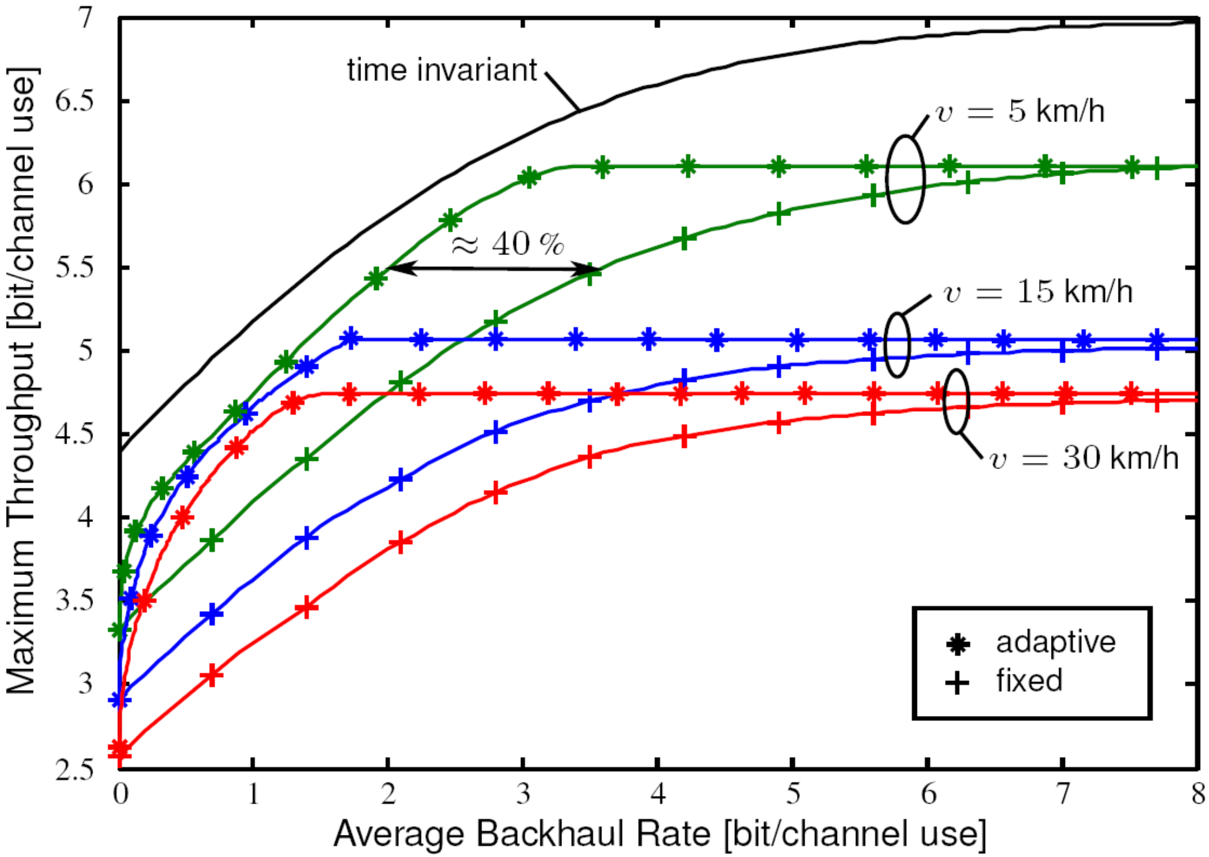
Fixed compression

- the same backhaul rate c_{fix} is used for the exchange of compressed signals

Adaptive compression

- take updated channel state information into account to decide, in ad hoc manner, which backhaul rate $c_{\mathrm{adapt}}[n]$ is sufficient for successful decoding
- limit the maximum backhaul rate that can be used for the exchange to c_{lim}

Ad Hoc CoMP with Adaptive Compression
Single Mobile Terminal



Comparison of maximum throughput over backhaul for the fixed and the adaptive scheme

$$f_c = 2.68\ \text{GHz},\ \sigma_v^2 = 0.1,\ P = 1$$

- We are interested in the maximum sum rate, which is achieved by successive interference cancellation (SIC)
- The decoding order is assumed to be fixed; MT a is always decoded first
- If the decoding of MT a is successful, the rates of both MTs are

$$r_{\mathrm{b}}[n,c] = \log_2 \left| 1 + P(\mathbf{h}_{\mathrm{b}})^H \left(\sigma_v^2 \mathbf{I} + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \sigma_{q,\mathrm{B}}^2 \end{bmatrix} \right)^{-1} \mathbf{h}_{\mathrm{b}} \right|$$

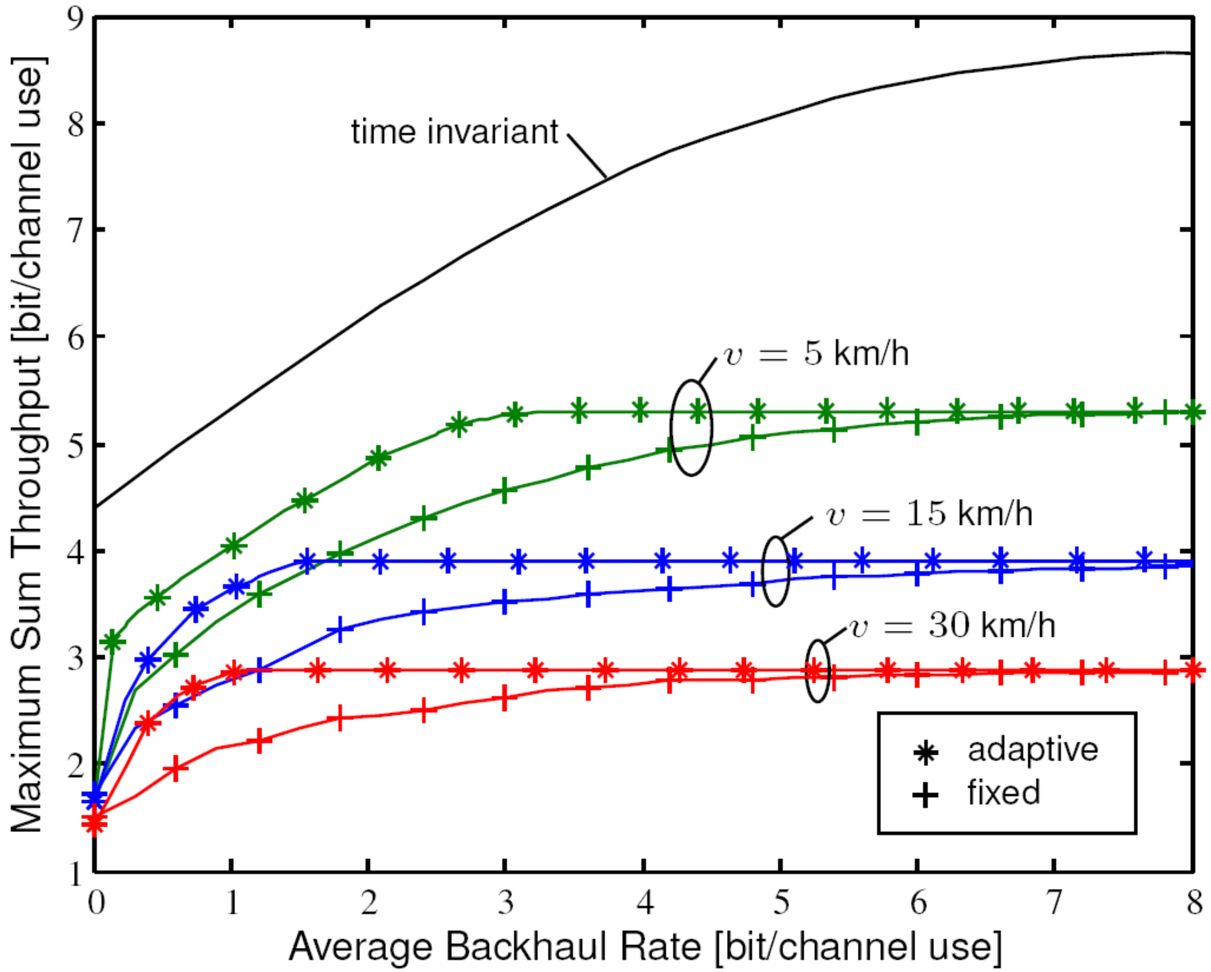
$$r_{\mathrm{a}}[n,c] = r_{\mathrm{sum}}[n,c] - r_{\mathrm{b}}[n,c]$$

Problems

- Even if one user can be decoded with low backhaul, the backhaul rate is increased until the other user is decoded as well
- Error propagation: If the first user cannot be decoded, the chance that the other user is in outage as well is strongly increased

Ad Hoc CoMP with Adaptive Compression

Two Mobile Terminals



$$f_c = 2.68\ \mathrm{GHz},\ \sigma_v^2 = 0.1,\ P = 1$$

Ad Hoc CoMP with Adaptive Compression

Conclusions and Future Work

Conclusions

- Employment of fixed backhaul rate is inefficient in terms of achievable throughput and the required backhaul rate
- By adapting the compression rate according to the channel state after transmission, we can use the backhaul much more effectively

Future Work

- Further work on the problem of backhaul rate minimization with rate constraints especially for the multi antenna base station case

M. Grieger, P. Marsch, G. Fettweis; *Ad Hoc Cooperation for the Cellular Uplink with Capacity Constrained Backhaul;* ICC 2010, Cape Town, SA

Contents

Ad Hoc CoMP with Progressive Compression

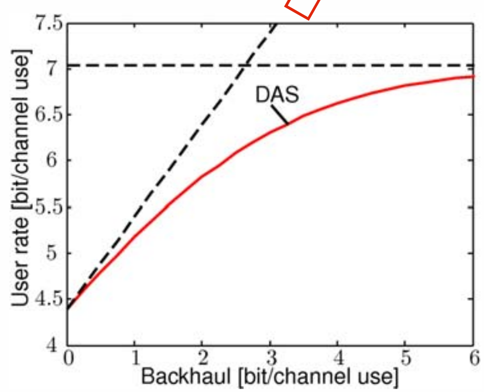
Problem Statement

TECHNISCHE UNIVERSITÄT DRESDEN

vodafone chair

- Scheduling and ad-hoc decoding process for DASs:

eNBs exchange CQI information → Master eNB schedules UEs to resources → Master eNB decides on quantization rate and decoding orders → Master eNB estimates achievable rates and determines MCS → Actual transmission → Exchange of quantized received signal to master eNB → Joint decoding of transmitted codewords



- **Problem**
  - When channel estimation errors occur, the decision on the compression rate cannot really be made.
- **Tradeoff**
  - High quantization accuracy → Low FER but large backhaul requirement
  - Low quantization accuracy → Relatively low backhaul requirement but high FER

Estimation error in block fading channels

$$\mathbf{E}[n] = \mathbf{H}[n] - \hat{\mathbf{H}}[n]$$

$$\hat{\mathbf{H}}[n] \perp \mathbf{E}[n] \;\Rightarrow\; E[\mathbf{H}[n]|\hat{\mathbf{H}}[n]] = \hat{\mathbf{H}}[n]$$

$$E\left[\mathrm{vec}(\mathbf{E}[n])\mathrm{vec}(\mathbf{E}[n])^H\right] = \sigma_{\mathrm{est}}^2\mathbf{I}$$

- n : transmission block index
- $\mathbf{E}$: channel estimation error matrix
- $\mathbf{H}$: channel matrix
- $\hat{\mathbf{H}}$: channel estimation matrix

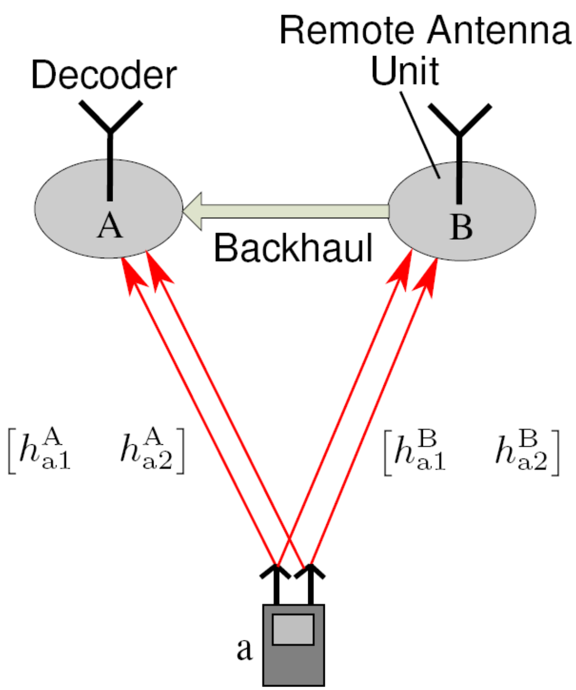
- Block fading channel with $\mathbf{H}$ and $\mathbf{E}$ fixed during the transmission of one codeword
- Non-optimality of Gaussian codebooks under imperfect channel estimation not considered

Channel estimation distortion

- Uncertainty in $\mathbf{E}$ leads to additional distortion with random variance
- Since the channel estimation error is constant for one codeword, the estimation distortion has random variance, depending on the realization of the channel estimation error

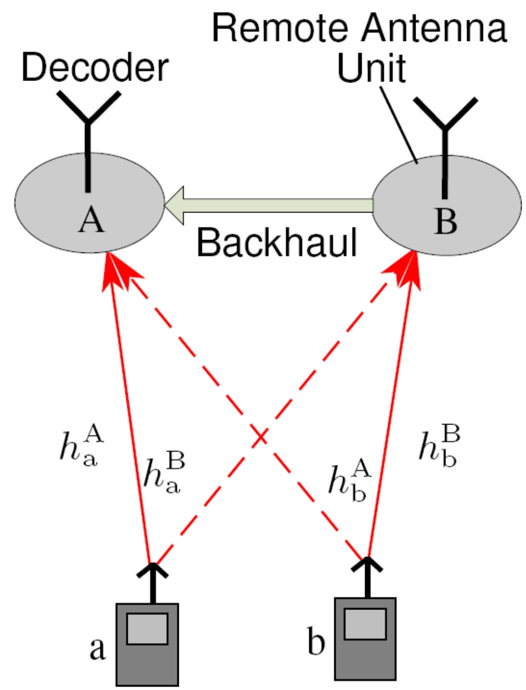
$$\mathbf{e} \sim \mathcal{NC}\left(\mathbf{0}, \mathbf{E}[n]\mathbf{P}\mathbf{E}^H[n]\right) = \mathcal{NC}\left(\mathbf{0}, \mathbf{\Phi}_{\mathbf{ee}}[n]\right)$$

System with one MT



$$\begin{bmatrix} y_A \\ \hat{y}_B \end{bmatrix} = \underbrace{\begin{bmatrix} \hat{h}^{A}_{a_1}[n] & \hat{h}^{A}_{a_2}[n] \\ \hat{h}^{B}_{a_1}[n] & \hat{h}^{B}_{a_2}[n] \end{bmatrix}}_{\hat{\mathbf{H}}[n]} \mathbf{x} + \underbrace{\mathbf{E}[n]\mathbf{x}}_{\mathbf{e}} + \begin{bmatrix} 0 \\ q_B \end{bmatrix} + \begin{bmatrix} v_A \\ v_B \end{bmatrix}$$

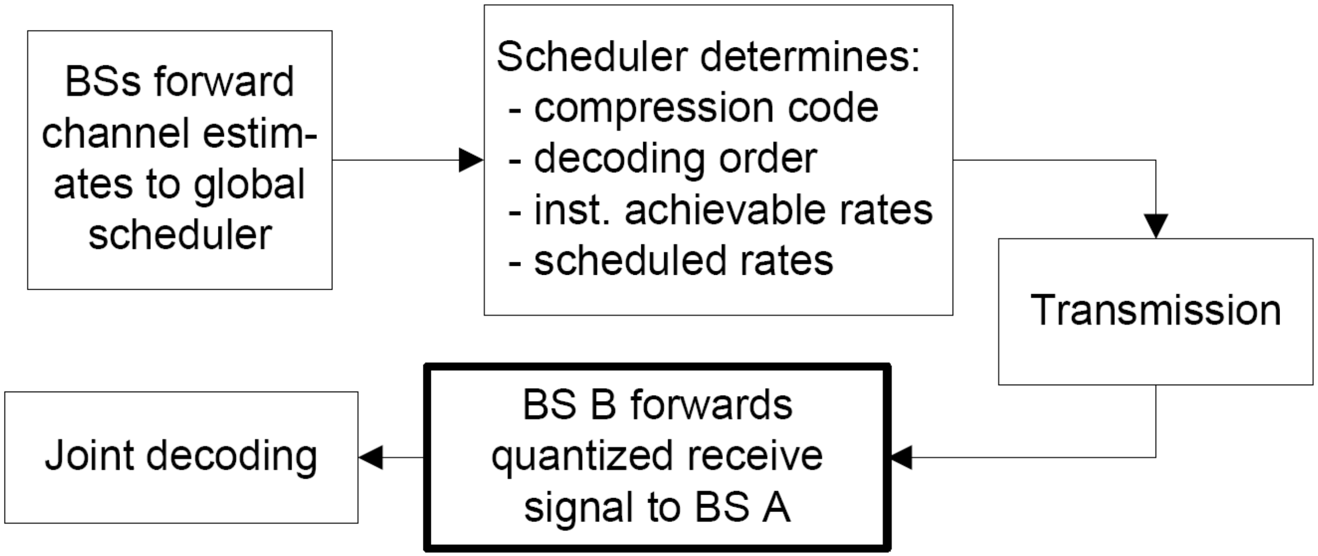
System with two MTs



$$\begin{bmatrix} y_A \\ y_B \end{bmatrix} = \underbrace{\begin{bmatrix} \hat{h}^{A}_{a}[n] & \hat{h}^{A}_{b}[n] \\ \hat{h}^{B}_{a}[n] & \hat{h}^{B}_{b}[n] \end{bmatrix}}_{\hat{\mathbf{H}}[n]} \mathbf{x} + \underbrace{\mathbf{E}[n]\mathbf{x}}_{\mathbf{e}} + \begin{bmatrix} 0 \\ q_B \end{bmatrix} + \begin{bmatrix} v_A \\ v_B \end{bmatrix}$$

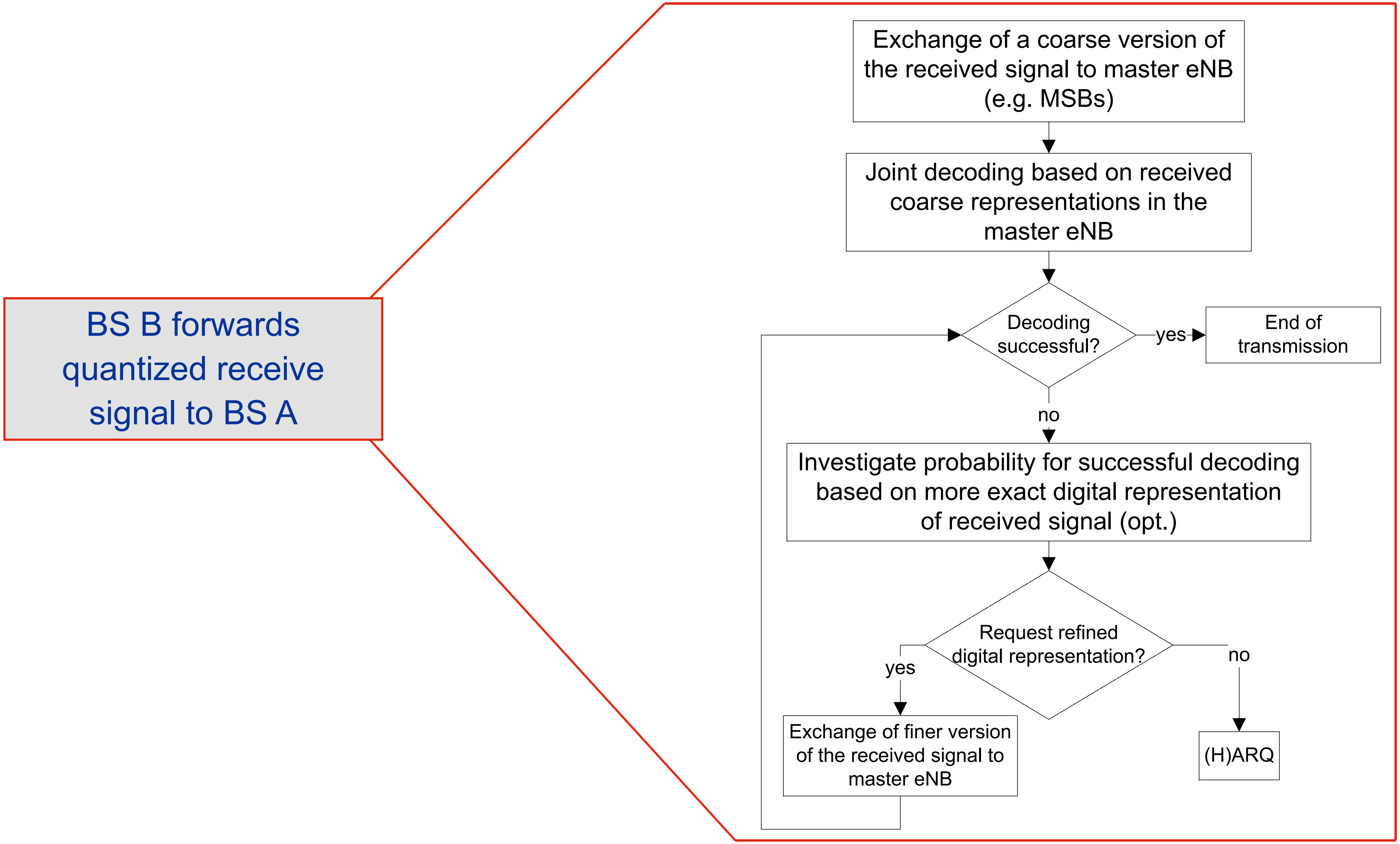
Ad Hoc CoMP with Progressive Compression

Scheduling and Progressive Ad hoc Cooperation



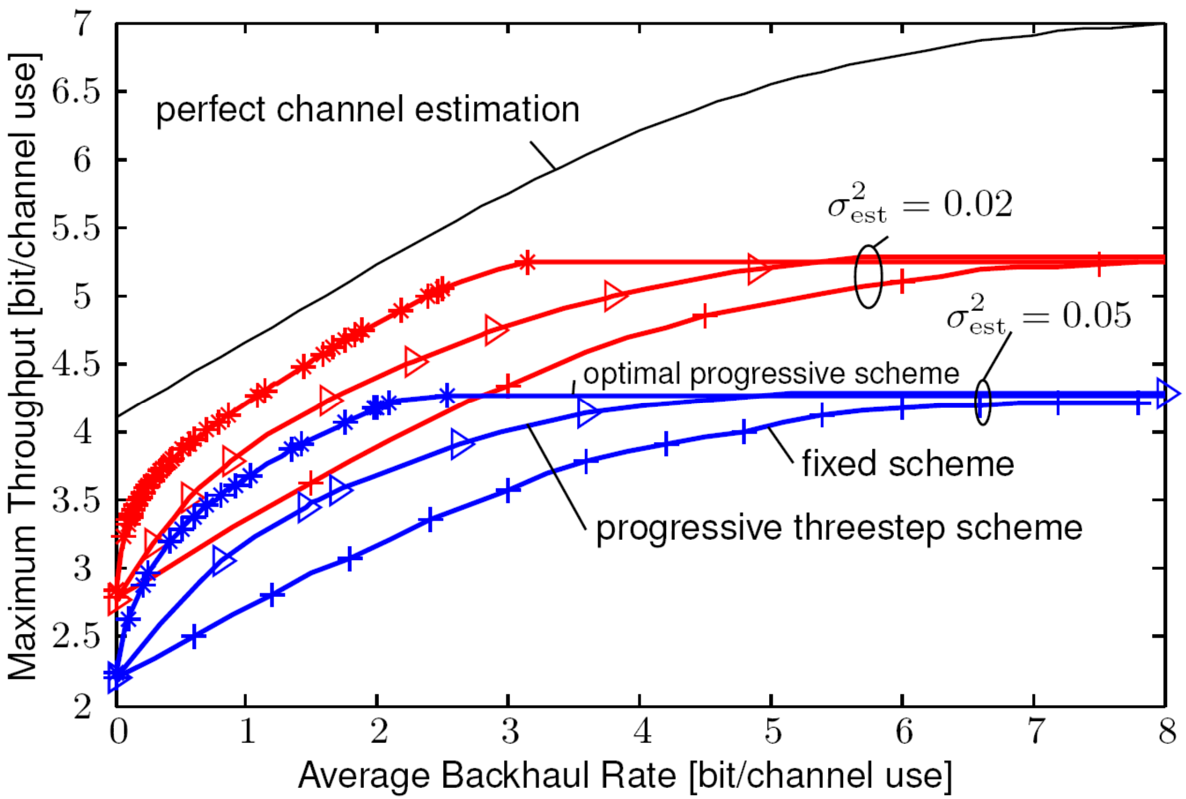
Block diagram of the scheduling and ad hoc cooperation process

Ad Hoc CoMP with Progressive Compression
Proposed Algorithm



Ad Hoc CoMP with Progressive Compression

System with One Mobile Terminal – Simulation Results



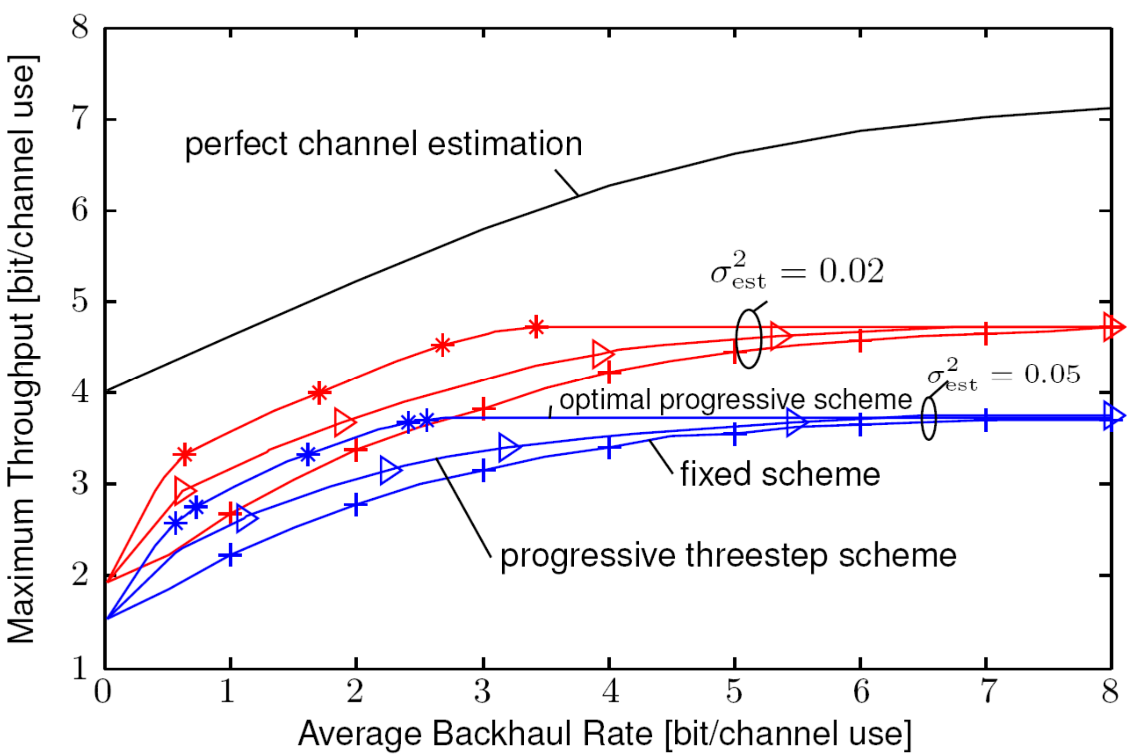
Comparison of maximum throughput over backhaul for the optimal and the heuristic three-step progressive scheme as well as the fixed scheme

$$(\sigma_v^2 = 0.1,\ P = 1)$$

Ad Hoc CoMP with Progressive Compression

System with Two Mobile Terminal – Simulation Results

vodafone chair



$$2 \text{ Users}, \ \sigma_v^2 = 0.1, \ \ P = 1$$

M. Grieger, P. Marsch, G. Fettweis; *Progressive Uplink Base Station Cooperation for Backhaul Constrained Cellular Systems;* SPAWC 2010, Marrakesh, Morocco

Contents

TECHNISCHE UNIVERSITÄT DRESDEN

vodafone chair

Summary & Future Work

TECHNISCHE UNIVERSITÄT DRESDEN

vodafone chair

Summary

- The main reason why transmission errors occur is imperfect CSI, we can differ
  - imperfect CSI due to scheduling delay: We propose to adapt compression accuracy after transmission (taken new channel information into account)
  - imperfect CSI due to channel estimation errors: We propose a progressive compression scheme that is based on refinable source codes.

Future work

- Include option of different cooperation schemes (e.g. distributed interference subtraction)
- Consider the cost of CSI exchange for scheduling
- Extend models to larger setups
- Work on cooperation cluster size
- Field test measurements
- System level simulations

Backoff

33. Treffen der VDE/ITG-Fachgruppe 5.2.4

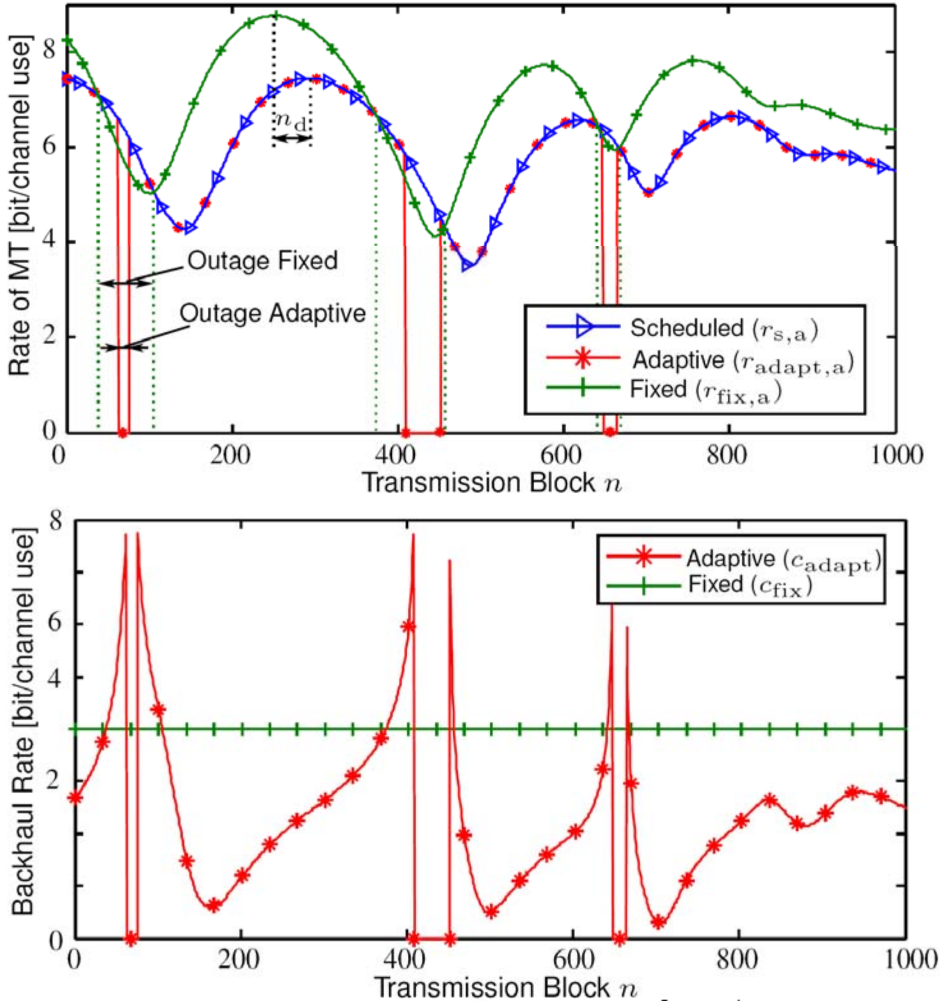
NEC, Heidelberg

July, 08 2010

Michael Grieger

DAS with Adaptive Compression

Single Mobile Terminal



$n_d = 45 \mathrel{\widehat{=}} 3\ \text{ms}$

$f_c = 2.68\ \text{GHz},\ \sigma_v^2 = 0.1,\ P = 1,\ v = 15\ \text{km/h}\quad c_{\text{lim}} = 8\ [\text{bit/channel use}],\ \Gamma = 0.15\quad T_s = \frac{1}{15\text{kHz}}$

Jake‘s spectrum used to model effects of the Doppler spread. $h_{a1,2}^m \sim \mathcal{NC}(0,1))$

DAS with Adaptive Compression

Performance Indicators

TECHNISCHE UNIVERSITÄT DRESDEN

vodafone chair

Average throughput & average backhaul

Fixed compression

$$T_{\text{fix},k}(c_{\text{fix}},\Gamma) = E_n\left[\mathbf{1}\left(r_{\text{s},k}[n,c_{\text{fix}},\Gamma] \leq r_{\text{fix},k}[n]\right) r_{\text{s},k}[n,c_{\text{fix}},\Gamma]\right], \qquad \bar{c}_{\text{fix}} = c_{\text{fix}}$$

Adaptive compression

$$T_{\text{adapt},k}(c_{\text{fix}},c_{\text{lim}},\Gamma) = E_n\left[\mathbf{1}\left(r_{\text{s},k}[n,c_{\text{fix}},\Gamma] \leq r_{\text{adapt},k}[n,c_{\text{lim}}]\right) r_{\text{s},k}[n,c_{\text{fix}},\Gamma]\right].$$

$$\bar{c}_{\text{adapt}} = E_n\left[c_{\text{adapt}}[n]\right]$$

Maximum throughput

Fixed compression

$$T^*_{\text{fix},k}(c = c_{\text{fix}}) = \max_{\Gamma:0\leq\Gamma\leq 1}, T_{\text{fix},k}(c_{\text{fix}},\Gamma),$$

Adaptive compression

$$T^*_{\text{adapt},k}(c) = \max_{c_{\text{fix}},c_{\text{lim}},\Gamma,\bar{c}_{\text{adapt}}\leq c} T_{\text{adapt},k}(c_{\text{fix}},c_{\text{lim}},\Gamma),$$

DAS with Adaptive Quantization

Achievable Data Rates and Optimal Compression

- The optimal compression scheme for the setup is Wyner-Ziv coding. The compression distortion can be modeled as additive i.i.d. zero-mean Gaussian noise

$$q_{\mathrm{B}} \sim \mathcal{NC}\left(0, \sigma^2_{q,\mathrm{B}}\right), \text{ where } \sigma^2_{q,\mathrm{B}}(c) = \frac{\sigma^2_{y,\mathrm{B|A}}}{2^c - 1}$$

- The conditional variance of the signal received at BS B is

$$\sigma^2_{y,\mathrm{B|A}} = \mathbf{h}_{\mathrm{B}}\left(\mathbf{I} + \mathbf{P}(\mathbf{h}_{\mathrm{A}})^H \left(\sigma_v^2 \mathbf{I}\right)^{-1} \mathbf{h}_{\mathrm{A}}\right)^{-1} \mathbf{P}(\mathbf{h}_{\mathrm{B}})^H + \sigma_v^2 \quad , \qquad \mathbf{h}_{\mathrm{B}} = \left[h^{\mathrm{B}}_{\mathrm{a}_1} \quad h^{\mathrm{B}}_{\mathrm{a}_2}\right]$$

- The maximum achievable rate is therefore

$$r_{\mathrm{a}}[n,c] = \log_2 \left| \mathbf{I} + \mathbf{P}\mathbf{H}^H \left(\begin{bmatrix} 0 & 0 \\ 0 & \sigma^2_{q,\mathrm{B}}(c) \end{bmatrix} + \sigma_v^2 \mathbf{I} \right)^{-1} \mathbf{H} \right|.$$

- For ad hoc cooperation, the problem of finding the minimum backhaul rate to successfully decode the transmitted data needs to be solved

$$\min_{\sigma^2_{q,\mathrm{B}}} \quad c_{\mathrm{adapt}}[n] = \log_2 \left(1 + \frac{\sigma^2_{y,\mathrm{B|A}}}{\sigma^2_{q,\mathrm{B}}}\right)$$

$$\text{s.t.} \quad \log_2 \left| \mathbf{I} + \mathbf{P}\mathbf{H}^H \left(\begin{bmatrix} 0 & 0 \\ 0 & \sigma^2_{q,\mathrm{B}} \end{bmatrix} + \sigma_v^2 \mathbf{I} \right)^{-1} \mathbf{H} \right| \geq r_{\mathrm{s,a}}[n]$$

Average Troughput

$$T_k(c, \hat{\mathbf{\Phi}}_{\mathbf{ee}}) = E_n\left[\mathbf{1}\Big(r_{\mathrm{s},k}(n, \hat{\mathbf{\Phi}}_{\mathbf{ee}}) \leq r_k(n,c)\Big) r_{\mathrm{s},k}(n, \hat{\mathbf{\Phi}}_{\mathbf{ee}})\right]$$

Average Backhaul Rate

$$\bar{c}_{\mathrm{fix}} = c_{\mathrm{fix}} \qquad \bar{c}_{\mathrm{pro}} = E_n\left[c_{\mathrm{pro}}[n]\right]$$

Maximum Throughput

$$T^*_{\mathrm{fix},k}(c_{\mathrm{fix}}) = \max_{\hat{\mathbf{\Phi}}_{\mathbf{ee}}} T_k(c_{\mathrm{fix}}, \hat{\mathbf{\Phi}}_{\mathbf{ee}}),$$

$$T^*_{\mathrm{pro},k}(\bar{c}_{\mathrm{pro}}) = \max_{E_n[c_{\mathrm{pro}}(n)] \leq \bar{c}_{\mathrm{pro}}, \hat{\mathbf{\Phi}}_{\mathbf{ee}}} T_k(c_{\mathrm{pro}}(n), \hat{\mathbf{\Phi}}_{\mathbf{ee}})$$

DAS with Progressive Compression

System with One Mobile Terminal

- Compression distortion given by rate distortion theory

$$\sigma_{q,\mathrm{B}}^2(c) = \frac{P(|\mathbf{h}_{\mathrm{a},1}^{\mathrm{B}}(n)|^2 + |\mathbf{h}_{\mathrm{a},2}^{\mathrm{B}}(n)|^2) + \sigma_v^2}{2^c} \qquad \mathbf{\Phi}_{\mathbf{qq}}(c) = \begin{bmatrix} 0 & 0 \\ 0 & \sigma_{q,\mathrm{B}}^2(c) \end{bmatrix}$$

- For a certain backhaul rate, the achievable rate of MT a is

$$r_{\mathrm{a}}(n,c) = \log_2 \left| \mathbf{I} + \hat{\mathbf{H}}(n)\mathbf{P}\hat{\mathbf{H}}^H(n) \left(\mathbf{\Phi}_{\mathbf{ee}}(n) + \mathbf{\Phi}_{\mathbf{qq}}(c) + \sigma_v^2 \mathbf{I} \right)^{-1} \right|$$

- The scheduled rate is determined based on the backhaul rate c_{fix} and on an assumption on the variance of the estimation distortion $\hat{\mathbf{\Phi}}_{\mathbf{ee}}$

$$r_{\mathrm{s,a}}(n, \hat{\mathbf{\Phi}}_{\mathbf{ee}}) = \log_2 \left| \mathbf{I} + \hat{\mathbf{H}}(n)\mathbf{P}\hat{\mathbf{H}}^H(n) \left(\hat{\mathbf{\Phi}}_{\mathbf{ee}} + \mathbf{\Phi}_{\mathbf{qq}}(c_{\mathrm{fix}}) + \sigma_v^2 \mathbf{I} \right)^{-1} \right|$$

- The transmission is successful, for a backhaul rate

$$r_{\mathrm{a}}(n,c) \geq r_{\mathrm{s,a}}(n, \hat{\mathbf{\Phi}}_{\mathbf{ee}})$$

- The minimum rate for which decoding is successful can be found by bisection.

CoMP with Progressive Compression

Scheduling

TECHNISCHE UNIVERSITÄT DRESDEN

vodafone chair

- We assume that resources are allocated in a way such that both MTs transmit on the same time and frequency resources
- The task of the scheduler is the assignment of scheduled transmission rates $r_{\mathrm{s},m}$, determined based on the available channel information $\hat{\mathbf{H}}$
- Transmission errors occur if the scheduled data rate $r_{\mathrm{s},m}$ is above the rate supported by the channel r_k

$$r_k[n,c] = I\left(y_\mathrm{A}, \hat{y}_\mathrm{B}; x_k | \hat{\mathbf{H}}[n], \mathbf{\Phi}_{\mathbf{ee}}[n], q_\mathrm{B}(c)\right).$$

- However, the BS do not know this rate, because the statistical properties of the estimation distortion are unknown
- The scheduler makes a guess on the estimation distortion $\hat{\mathbf{\Phi}}_{\mathbf{ee}}[n] = \hat{\mathbf{E}}[n]\mathbf{P}\hat{\mathbf{E}}^H[n]$
- Hence, the scheduling task is to choose $\hat{\mathbf{\Phi}}_{\mathbf{ee}}(n)$ such that the throughput is maximized.
- We add the constraint that the scheduler assumes that always the same backhaul rate c_{fix} is used for compression.

$$r_{\mathrm{s},k}(n, \hat{\mathbf{\Phi}}_{\mathbf{ee}}) = I\left(y_\mathrm{A}, \hat{y}_\mathrm{B}; x_k | \hat{\mathbf{H}}(n), \hat{\mathbf{\Phi}}_{\mathbf{ee}}, q_\mathrm{B}(c_{\mathrm{fix}})\right)$$

CoMP with Progressive Compression

Ad hoc Cooperation

TECHNISCHE UNIVERSITÄT DRESDEN

vodafone chair

Progressive ad hoc Cooperation

- When the variance of the channel estimation distortion is unknown, we do not know the quanization accuracy that is required to successfully decode the transmitted information
- A possible solution relies on
  - error detection coding schemes that indicate the decoding success (e.g. CRC check)
  - successively refinable source coding schemes
- The main idea is to progressively increase the compression rate c, hence c_1, c_2, ... until

$$r_k[c_i] \geq r_{\mathrm{s},k}[c_{\mathrm{fix}}]$$

Problem: Each iteration comes at the cost of delay and processor power

How to choose the backhaul rate sequence optimally ?