Pragmatic Adaptive Transmission for Multiuser MIMO–OFDMA Systems

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Introduction

- Research interest of Digital Communications Lab

  - Cell planning technique for cell throughput enhancement
  - Iterative receiver and AMC for cooperative diversity system
  - Adaptive transmission under mobility and limited feedback
  - MIMO channel coding
Introduction

- Multiuser MIMO OFDMA System

- Aim is to maximize the cell throughput
- Various mobile speed and various status
- Limited feedback resource

→ Utilizing appropriate scheme for various status is required !!
Introduction

- Capacity of closed loop MIMO–OFDMA Downlink systems [1]

\[
C_{\text{MIMO-OFDMA}} = E \left[ \max_{\sum_{n=1}^{N_s} \text{Tr}(Q_n) = \sum_{n=1}^{N_s} \sum_{k=1}^{K} \text{Tr}(Q_{k,n}) \leq P} \frac{1}{N_s} \sum_{n=1}^{N_s} \log_2 \left| I_{N_t} + \sum_{k=1}^{K} H_{k,n} Q_{k,n} H_{k,n}^H \right| \right] \text{[bps/Hz]}
\]

- How can we obtain the throughput as large as possible with the minimum amount of feedback?
- What is the relationship between throughput and key parameters?
Introduction

- For high speed mobile stations
  - High time selectivity
  - Comb type sub-channel
  - Tracking the channel variation is an important issue
    - Channel prediction

- For low speed mobile stations
  - Band type sub-channel
  - Sub-channel allocation based on CSI is an important issue
    - The more CSI, the higher performance but the higher overhead
    - Efficient feedback scheme is required
Comb Type Sub-channel AMC
Comb Type Sub-channel AMC

[2] proposed an adaptive transmission technique based on LLR distribution as the CSI for LDPC coded OFDM cellular systems

- CSI is composed of the mean and variance of the LLR distribution
- With a little more feedback bits, 2~3 dB throughput gain obtained

![Graph showing average throughput vs. average E_s/N_0 dB](image)

- Power allocation and MCS selection algorithm is proposed
- 2~5dB gain in multiuser environment

Initialize:

\[ P^+(s) = P_T(i(j^*(s)) + 1, j^*(s)) - P_T(i(j^*(s)), j^*(s)) \]
\[ P^-(s) = P_T(i(j^*(s)), j^*(s)) - P_T(i(j^*(s)) - 1, j^*(s)) \]
\[ \Delta r(i) = r(i + 1) - r(i) \]
\[ P_T(I + 1, j) = \infty, P_T(0, j) = 0 \]
\[ P_r = P_T - \sum_{s=1}^{S} P_T(i(j^*(s)), j^*(s)) \]

While

\[ \mu^- = \arg \max_s \Delta P^-(s), \mu^+ = \arg \min_s \Delta P^+(s) \]

If \( \Delta P^+(\mu^+) \leq P_r \)

\[ P_r = P_r - \Delta P^-(\mu^+), i(j^*(\mu^+)) ++ \]

Update \( \Delta P^+(\mu^+), \Delta P^-(\mu^-) \)

elseif \((\Delta r(i(j^*(\mu^+))) > \Delta r(i(j^*(\mu^-)) - 1) \land \Delta P^+(\mu^+) < P_r + \Delta P^-(\mu^-)) \) or

\( \Delta r(i(j^*(\mu^+))) \) \( = \Delta r(i(j^*(\mu^-)) - 1) \land \Delta P^+(\mu^+) < \Delta P^-(\mu^-)) \)

\[ P_r = P_r - \Delta P^-(-\mu^-) - P^+(\mu^+) \]
\[ i(j^*(\mu^-)) - , i(j^*(\mu^+)) ++ \]

Update \( P^+(\mu^+), P^-(\mu^+), P^+(\mu^-), P^-(\mu^-) \)

else break

endif

end while
Channel Prediction

- Effect of the channel variation
  - The actual transmission based on the CSI occurs after some delay
    - During the total delay, channel varies
    - The higher mobility, the more variation
  - CSI imperfectness results in performance degradation

- Channel prediction
  - Rather than directly using the estimated channel value, use a predicted value
    - However, the predicted value contains error term
    - The error variance increases as the mobility increases

- A new scheme
  - Predicted value as a short-term CSI
  - The prediction error variance as a long-term CSI
    - Compensate the performance degradation due to the error
System Model

- Error-free feedback channel
- Rayleigh fading channel
- M by N MIMO
At the Receiver

- **Short-term CSI**
  - Predicted receive SNR (eliminate the bias term)

\[
\tilde{\gamma} = \frac{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} |\hat{a}_{i,j}|}{\sigma_w^2} \quad \hat{\gamma} = \tilde{\gamma} + E\{\gamma - \tilde{\gamma}\}
\]

where

- \(\hat{a}_{i,j}\): predicted value of each channel
- \(\sigma_w^2\): noise variance

- **Long-term CSI**
  - Error variance of the predicted receive SNR

\[
\sigma_{\tilde{\gamma}}^2 = E\{(|\hat{\gamma} - \gamma|^2)\}
\]

- The real receive SNR can be obtained after the actual transmission
  - Long-time moving average

- Reporting period is much longer than the short-term CSI
  - Negligible overhead
At the Transmitter

- **Average PER**

\[
P_{e,i}(\gamma, P_T) = E\{PE_{e,i}(\gamma) | \hat{\gamma}\} = \int_{-\infty}^{\infty} a_i \exp\left(-b_i \frac{\gamma P_T}{P_{\text{pilot}}}\right) f(\gamma | \hat{\gamma}) d\lambda
\]

\[
P_{e,i}(P_T, e) = \left[1 - Q_K\left(\sqrt{2\hat{\gamma}\rho - K}, \sqrt{2\gamma_{th,i} \rho}\right)\right]
\]

\[+ a_i \left(\frac{1}{1+b_i \rho \Delta P_T}\right)^K \exp\left(-\frac{b_i \Delta P_T (\hat{\gamma} - K \rho)}{1+b_i \rho \Delta P_T}\right)
\]

\[\cdot Q_K\left(\sqrt{2\hat{\gamma}/\rho \Delta P_T - K}, \sqrt{2\gamma_{th,i} (1+b_i \rho \Delta P_T)} / \rho\right)
\]

\[
\rho = \sigma_e^2 / \sigma_w^2 \quad \Delta P_T = P_T / P_{\text{pilot}} \quad K = MN
\]

Take average of the instantaneous PER over the all possible range of true SNR

For a given target PER and CSI, the Tx power can be searched

Then, the MCS selection of the \(j\)-th user is done as

\[
i(j) = \arg \max_{i} r(i)
\]

subject to \(P_T(i, j) \leq P_A / S\)

\(r(i)\) : the rate of the \(i\)-th MCS

\(P_A\) : total power

\(S\) : # of user
Adaptive Modulation and Coding

- **Drawback**
  - Calculation of the average PER formula is burdensome
  - Not appropriate for real time application

- **Efficient Tx power calculation method**
  - Recall, $\rho = \sigma_e^2 / \sigma_w^2$ and $\hat{\gamma} = \bar{\gamma} + E\{\gamma - \bar{\gamma}\}$

**Linear approximation as**

$$P_t(\hat{\gamma}, c_L) \approx m_i(c_L) \hat{\gamma} + n_i(c_L) \quad (dB)$$

where

$$m_i(c_L) = \frac{\hat{\gamma}_2(c_L) - \hat{\gamma}_1(c_L)}{P_{T,2}(c_L) - P_{T,1}(c_L)}$$

$$n_i(c_L) = -m_i(c_L) P_{T,1}(c_L) + \hat{\gamma}_1(c_L)$$

Pick two points from available range of $\hat{\gamma}$ appropriately s.t.

$$(\hat{\gamma}_1(c_L), P_{T,1}(c_L)) \quad (\hat{\gamma}_2(c_L), P_{T,2}(c_L))$$

$\hat{\gamma}_1(c_L) < \hat{\gamma}_2(c_L)$$
Simulation Results

- PER performance
  - 2x2 MIMO, 8th MCS option
    - is product of the maximum-Doppler-freq. and the prediction step

Target PER is obtained well

![Graph showing PER performance for different conditions and schemes.](image)

Conventional schemes do not meet the target PER.
Simulation Results

- **Throughput results**
  - 20 user, 12 sub-channels, 6 equal-gain channels
  - Low mobility

  i) Near the ‘perfect SNR’ case when low mobility

  ii) ‘Linear approx’ shows no performance loss

Even worse than ‘Fixed power’ scheme
Simulation Results

- Throughput results
  - 20 user, 12 sub-channels, 6 equal-gain channels
  - High mobility

Approaches the ‘Fixed power’ case as mobility increases

Worse than fixed power case even at low SNR
Feedback Resource Allocation Strategy

- Simulation results
  - The amount of feedback reduction
  - If the distribution of the mobility among users, \( f_X(x) \), is given,

\[
f_{\text{red}} = P\{\eta > \delta\} = \sum_{(x_{1,j}, x_{2,j}) \in U} \int_{x_{1,j}}^{x_{2,j}} f_X(x)dx
\]

\( \delta \): threshold

\( U \): the set of all disjoint intervals in which \( \eta > \delta \)

- Normalized PENR

\[
\eta = \frac{K\rho}{E\{\gamma\}}
\]

Feedback reduction versus threshold value

More than 50% reduction available

Cell Throughput - 12ch./20user, 6 equal-gain channels (Mixed mobility)

Negligible degradation

Throughput (Mbps)
Band Type Sub-channel AMC
Motivation

- Multi-user MIMO-OFDMA Down Link

- We want to obtain the maximum throughput by means of opportunistic scheduling with adaptive power and rate control.
- The average system capacity increases with the number of active users in a cell.
- However, the amount of feedback for scheduling and adaptive rate control also increases with the number of users.
System Model

- Band-Closed loop MIMO-OFDMA Downlink system model

\[ C_{FCQI} = E \left[ \frac{1}{N_b} \sum_{i=1}^{N_a} \sum_{j=1}^{N_b} \log_2 \left( 1 + \max_{k \in K} | h_{k,i,j} |^2 \frac{E_s}{N_o} \right) \right] \]

(with equal power allocation assumption)

- We assign each subchannel to the user with the highest channel quality.
- By applying SDMA with OS as a MIMO technique at each subchannel in OFDMA systems, we can obtain additional multiuser diversity in the spatial domain (OFSDMA).
Full CQI Feedback scheme

- Full CQI feedback scheme can give the maximum average system capacity, but requires $N \times N_q \times K$ as the amount of feedback.
- It can be impractical, especially when the time selectivity and the frequency selectivity are not very low.

![Graph showing the relationship between average system capacity and SNR with different values of $K$. The graph illustrates that the average system capacity increases with the number of active users.]

![Graph showing the relationship between the amount of feedback and the number of users. The graph illustrates that the amount of feedback also increases with the number of users.]

Average system capacity increases with the number of active users.

The amount of feedback also increases with the number of users.
Partial CQI Feedback Scheme [4]

- Each user reports CQI on partial subchannels having the highest CQI. Although it can provide better performance than a round-robin scheduling with partial CQI, it did not take the empty subchannel problem fully into account.
- Although it can reduce the amount of feedback as

\[
N_{PCQI} = \left( \left\lceil \log_2 N \right\rceil + N_q \right) N_p + N_q \right) \times K,
\]

it shows the considerable performance degradation.
Two-Step Partial CQI Feedback Schemes [5]


This scheme is designed for the systems where a base station initially selects the fixed number of users and assigns an equal number of subchannels per user based on the average CQI value of each user.
Partial CQRI (Channel Quality Rank Information) Feedback Schemes [6]

- First, all users report partial subchannel indices in the order of CQI rank as the first feedback. Using them, a base station allocates each non-empty subchannel to the user with the highest rank, offering multiuser diversity.
- For the scheduling of empty subchannels, a round robin scheduling can be used.
- After a base station broadcasts the user selection information, only selected users report CQI of the selected subchannels to the base station as the second feedback.
Capacity Analysis

Assumption

- ZF receiver is used in each receiver.
- The number of antenna: $N_t = N_r (= N_a)$
- MIMO channel model with i.i.d. complex Gaussian random variables with zero mean and unit variance
- Block fading channel model in both time and frequency domains
- Equal power allocation to all subchannels ($\rho = E_s / N_o$)
- Then, the pdf of the CQI (SNR) on each subchannel is given by

$$f_{X_{k,n}}(x) = \frac{N_a}{\rho} e^{-\frac{x N_a}{\rho}} , \quad x > 0.$$ 

Order Statistic

$$f_{Y_{N,n}}(y) = \frac{N!}{(n-1)! (N-n)!} \sum_{m=0}^{n-1} \binom{n-1}{m} (-1)^m e^{-y \frac{N_a}{\rho} (N-n+m+1)}$$ 

$$C_N(n) = E[\log_2 (1 + Y_{N,n})]$$ 

$$= \int_0^\infty \log_2 (1 + y) f_{Y_{N,n}}(y) dy$$ 

$$= \frac{N!}{(n-1)! (N-n)!} \sum_{m=0}^{n-1} \frac{1}{N-n+m+1} \binom{n-1}{m} (-1)^m$$ 

$$\log_2(e) e^{\frac{N_a}{\rho} (N-n+m+1)} E_1 \left( \frac{N_a}{\rho} (N-n+m+1) \right)$$ 

where $E_1(x) = \int_x^\infty e^{-t} t^{-1} dt$
Capacity Analysis

- **Full CQI Feedback Scheme**
  \[
  C_{FCQI} = E \left[ \frac{1}{N_s} \sum_{i=1}^{N_s} \sum_{j=1}^{N_s} \log_2 \left( 1 + \max_{k \in \mathcal{K}} X_{k,i,j} \right) \right] \\
  = E \left[ \frac{1}{N_b} \sum_{n=1}^{N} \log_2 \left( 1 + \max_{k \in \mathcal{K}} X_{k,n} \right) \right] \quad \text{• The maximum CQI}
  \]

- **Partial CQI Feedback Scheme**
  \[
  C_{PCQI} = E \left[ \frac{1}{N_b} \sum_{n=1}^{N} \left\{ p(R_n = 1) \log_2 \left( 1 + \max_{k \in \mathcal{K}} X_{k,n} \right) \right\} \\
  + p(R_n = 0) \log_2 \left( 1 + \max_{k \in \mathcal{K}} \left( \min_{n^* \in \mathcal{N}} X_{k,n^*} \right) \right) \right] \\
  \quad \text{• Non-empty subchannel case} \\
  \quad \text{→ The maximum CQI} \\
  \quad \text{• Empty subchannel case} \\
  \quad \text{→ The maximum value among all users’ minimum CQI}
  \]

- **Partial CQRI Feedback Scheme**
  \[
  C_{PCQRI} = E \left[ \frac{1}{N_b} \sum_{n=1}^{N} \left\{ p(R_n = 1) \log_2 \left( 1 + X_{\arg \max_{k \in \mathcal{K}} (r_k)} \right) \right\} \\
  + p(R_n = 0) \log_2 \left( 1 + \text{rand}(K) \right) \right] \\
  \quad \text{• Non-empty subchannel case} \\
  \quad \text{→ The maximum CQRI} \\
  \quad \text{• Empty subchannel case} \\
  \quad \text{→ Round-robin}
  \]
# Capacity Analysis

<table>
<thead>
<tr>
<th></th>
<th>The Average System Capacity</th>
<th>The Amount of Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FCQI</strong></td>
<td>$C_{\text{FCQI}} = N_a C_K(K)$</td>
<td>$N_{\text{FCQI}} = N N_q K$</td>
</tr>
<tr>
<td><strong>PCQI</strong></td>
<td>$C_{\text{PCQI}} = N_a \left[ \frac{1}{N_p} p(K_r=1) \sum_{n=N-N_r+1}^{N} C_N(n) + \sum_{r=2}^{K} p(K_r=r) c_1 \sum_{n \in N} \sum_{m \in M(n)} c_2 c_3 \sum_{l \in L} c_4 e^{c_5} \frac{1}{c_5} E_1(c_5) \right.$</td>
<td>$N_{\text{PCQI}} = \left[ (\lceil \log_2(N) \rceil + N_q) N_p + N_q \right] K$</td>
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<td>$\left. + \left( 1 - \frac{N_p}{N} \right)^K K N N_a \frac{\log_2(e)}{\rho} \sum_{m=0}^{K-1} (-1)^m e^{c_6} \frac{1}{c_6} E_1(c_6) \right]$</td>
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<tr>
<td></td>
<td>$ - c_1, ..., c_6 \text{ is omitted.}$</td>
<td></td>
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<tr>
<td><strong>PCQRI</strong></td>
<td>$C_{\text{PCQRI}} = N_a \left[ \sum_{n=N-N_p+1}^{N} \sum_{r=1}^{K} p(q=n</td>
<td>K_r=r) p(K_r=r) C_N(n) \right.$</td>
</tr>
<tr>
<td></td>
<td>$\left. + \left( 1 - \frac{N_p}{N} \right)^K \frac{1}{N - N_p} \sum_{n=1}^{N-N_p} C_N(n) \right]$</td>
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</table>
Performances

- When $K = 100$, PCQRI achieves 90% capacity of FCQI, requiring only 4% and 60% feedback rate of FCQI and PCQI.

- The performance improvement of PCQRI over the conventional PCQI comes from its feedback rate efficiency as well as the two step feedback procedure to solve the empty subchannel problem.

![Graph](image)

- The feedback rate can be reduced significantly by using PCQRI.

![Graph](image)

- PCQRI outperforms at a low feedback rate region.

Maximum achievable capacity at a given feedback amount:

- $SNR = 10dB$, $N_0 = 1024$, $N_b = 32$, $N_c = 32$, $N_a = 4$
Throughput optimization

- The best feedback scheme can be changed according to the environmental factors such as time and frequency selectivity, delay constraints.
- Optimization problem for the maximization of downlink throughput per total bandwidth

\[
W_1 = \frac{N_{s,DL}}{T} \text{ [Hz]}, \quad W_2 = \frac{N_{s,UL}}{T} = \frac{1}{T} \left[ \frac{N_{\text{feedback}}}{C_{UL} \cdot N_{OFDM} \cdot N_a} \right] \text{ [Hz]}
\]

where \( C_{UL} = E \left[ \log_2 \left( 1 + SNR_{UL} \right) \right] \)

Then,

\[
S = \frac{C_{DL} W_1}{W_1 + W_2} = \frac{C_{DL} \left( N_{s,DL} / T \right)}{\left( N_{s,DL} / T \right) + \left( N_{s,UL} / T \right)} = \frac{C_{DL} N_{s,DL}}{N_{s,DL} + N_{s,UL}}
\]

\[
= \frac{C_{DL} N_{s,DL}}{N_{s,DL} + \left[ \frac{N_{\text{feedback}}}{C_{UL} \cdot N_{OFDM} \cdot N_a} \right]} \text{ [bps / Hz]}
\]
Throughput optimization

- According to the time selectivity, the best feedback scheme and its optimal number of reported subchannel can be changed.

When the time selectivity is quite large, PCQRI feedback scheme requiring the least feedback rate gives the maximum throughput with the optimal solution.

When the time selectivity is relatively small, FCQI feedback scheme requiring the largest feedback rate gives the maximum throughput.
Throughput optimization

- As the time selectivity of the channel becomes small, the downlink throughput per total bandwidth increases due to the reduced feedback rate per TTI.
- At a high-time selectivity region, PCQRI feedback scheme outperforms than others.
- When the number of subchannel becomes less than a certain threshold, PCQRI feedback scheme causes the performance degradation due to its CQRI based user selection.
References


