Dynamic Multiuser Resource Allocation and Adaptation for Wireless Systems

Khaled Ben Letaief
Chair Professor and Head
Department of Electronic and Computer Engineering
The Hong Kong University of Science and Technology

The Hong Kong University of Science & Technology

• The university opened in 1991
  - Consists of four schools
  - Offers academic programs at undergraduate, master and doctoral levels

• HKUST Academic System
  - Credit based continuous assessment system used by North American universities
  - Faculty retention and promotion system similar to North American universities
  - Faculty is expected to perform research, teaching and service
  - English Instruction

ECE Department: State-of-the Facilities
**ECE Faculty Background**

Mostly educated in North America

- UC Berkeley 7
- Stanford 5
- Toronto 4
- U. Wash. Seattle 4
- U. Illinois, Urbana C. 3
- U. Southern California 3
- Harvard 3
- Princeton 2
- Columbia 2
- Yale 2
- Purdue 1

**Overseas Exchange Program**

- Enhances students’ exposure in overseas universities w/o delaying graduation (One semester in Mainland and two semesters Overseas)
- Some of our partners
  - Univ. of Pennsylvania, UCLA, USA
  - UC Berkeley, Georgia Tech, MIT, Rice, USA
  - Rice Univ., USA
  - U. of Toronto, U. of Waterloo, Canada
  - Univ. of Sydney, Australia
  - Chalmers University of Technology, Sweden
  - Ecole des Mines de Nantes, France
  - INT, France
  - Technical U. of Denmark, Denmark
  - U. of Bath, UK
  - Chinese universities
    - Peking University, Fudan U., Tsinghua, Shanghai Jiaotong U., Hongkong U.

**International Recognition**

- IEEE Grade of Fellow is one of the Institute’s most prestigious honors
- Comparison between some countries in Asia-Pacific (as of 16/1/03)

<table>
<thead>
<tr>
<th>Country</th>
<th>No. Fellows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>35</td>
</tr>
<tr>
<td>Taiwan</td>
<td>35</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>28</td>
</tr>
<tr>
<td>India</td>
<td>26</td>
</tr>
<tr>
<td>China</td>
<td>23</td>
</tr>
<tr>
<td>Korea</td>
<td>18</td>
</tr>
<tr>
<td>New Zealand</td>
<td>3</td>
</tr>
</tbody>
</table>

**ECE Department at HKUST has 11 IEEE Fellows as of December 2006**
HKUST among World’s Best Technology Universities
HKUST has been ranked number 17 by The Times Higher Education Supplement (THES) in its league table of the World’s Top 100 Technology Universities, and number ONE university in Hong Kong.

Newsweek ranks HKUST at #60 globally! (Aug., 2006)

- Global Top 100 Ranking takes into account openness and diversity, as well as distinction in research.
- UST is #1 in HK at #60, with HKU at #69 and CU at #96.
- Youngest University in the list of Global Top 100.
- Not a single other Mainland Chinese university made the Global Top 100.

Motivation and Background

Data Rate

It is not just about data rate!

Delay

It is about Quality of Service!
**Challenges**

- High Data Rate, seamless and high mobility requirements
- Spectral efficiency challenge (2 – 10 b/s/Hz)
- Frequency selectivity due to large bandwidth requirements
- High System Capacity
- Seamless coverage and support across different networks, devices, and media forms
- Reliable Communications
  - Harsh wireless channel
  - Scarce radio spectrum
  - Energy constraint

**Cross-layer Optimization and Resource Allocation**

- High Spectral Efficiency
- High Energy Efficiency
- Overall good performance


**Outline**

- Introduction to OFDM and MIMO
- Introduction to dynamics in wireless communications systems
- Dynamic resource allocation
  - SISO-OFDM systems
  - MIMO-OFDM systems
- Cross-layer design and optimization
  - Joint MAC-PHY resource allocation
  - Joint design of PHY and networking or application layers

**OFDM**

- OFDM: Orthogonal Frequency Division Multiplexing
- Converts a wideband frequency selective fading channel into a parallel collection of narrow band frequency flat sub-channels
  - Robust against fading, ISI, and narrowband interference
  - Can be implemented by discrete FFT
Higher transmission rate (multiplexing gain)
Higher link reliability (diversity gain)
Wider coverage

Capacity of MIMO channel increases linearly with the number of antennas at both sides

Applications of MIMO and OFDM in WLAN
- Orthogonal frequency division multiplexing (OFDM)
- Multiple antenna techniques (MIMO)
Dynamics in Wireless Communications Systems – Channel Variation

• Wireless channel varies dramatically over time, frequency, and space

Link Adaptation

• Adaptive modulation
  - Data rate: $\log_2(1 + \gamma_n P_n)$
  - $\gamma_n$: Effective channel gain on subchannel $n$
  - $P_n$: Transmit power on subchannel $n$
• Optimal power allocation:
  Water filling
  $$P_n = \begin{cases} \frac{1}{\gamma_n} & \gamma_n \geq 1 \\ \frac{1}{\gamma_n} \lambda + \frac{1}{\gamma_n} \lambda & \text{otherwise} \end{cases}$$

Dynamics in Wireless Communications Systems – Multiuser Diversity

• Channel attenuations of different users are mutually independent
• Frequency and time domain channels can be dynamically allocated to users
• Examples:
  - Dynamic subcarrier allocation
  - Opportunistic scheduling
Dynamics in Wireless Communications Systems

- Impact of PHY layer characteristics on the upper layers
  - Time-varying channel capacity
  - Time-varying connectivity and topology
  - User mobility

Obstacles or Opportunities?

Outline

- Introduction to OFDM and MIMO
- Introduction to dynamics in wireless communications systems
- Dynamic resource allocation
  - SISO-OFDM systems
  - MIMO-OFDM systems
- Cross-layer design and optimization
  - Joint MAC-PHY resource allocation
  - Joint design of PHY and networking or application layers

Problem Formulation

- $r_{k,n}$: data rate of user $k$ on subcarrier $n$
- $p_{k,n}$: transmit power of user $k$ on subcarrier $n$
- $c_{k,n}$: subcarrier allocation indicator of user $k$ on subcarrier $n$
- $h_{k,n}$: channel coefficient of user $k$ on subcarrier $n$
- $R_k$: minimum data rate requirement of user $k$, if any

$$p_{k,n} = \frac{f(r_{k,n})}{p_{k,n}} \text{ for } k, n$$
**Problem Formulation**

- Maximizing data rate for a given power budget and a target BER:

\[
\max \sum_{n=1}^{N} \sum_{k=1}^{K} c_{n,k} r_{n,k}
\]

Subject to:

\[
\sum_{k=1}^{K} c_{n,k} p_{k,n} \leq P_{\text{tot}}
\]

\[
\sum_{k=1}^{K} c_{n,k} = 1 \quad \text{for all } n
\]

\[
c_{n,k} \in \{0,1\}
\]

- Minimizing total transmit power for a given data rate and BER

\[
\min \sum_{n=1}^{N} \sum_{k=1}^{K} c_{n,k} p_{k,n}
\]

Subject to:

\[
\sum_{n=1}^{N} c_{n,k} r_{n,k} \geq R_k \quad \text{for all } k
\]

\[
\sum_{n=1}^{N} c_{n,k} = 1 \quad \text{for all } k
\]

\[
c_{n,k} \in \{0,1\}
\]

**Intra- and Inter-cell Adaptation for SISO-OFDM**

- We have considered SISO-OFDM adaptive resource allocation in a single cell

- What about a multi-cell system?
  - Adaptive cell selection


- A mobile is adaptively associated to a cell based on
  - Resource availability in the candidate cells
  - Amount of resources that have already been assigned
  - Amount of resources that is necessary to satisfy the investigated user’s QoS
  - Intra-cell adaptation affects the resource occupancy
Performance Improvement: Subcarrier-and-Bit Allocation

- 4 users
- 128 subcarriers
- Minimal data rate
  - 2 users: 128 bits/OFDM
- BER requirement: $10^{-4}$
- Cell radius: 1km
- Path loss exponent: 4
- Std of log-normal shadowing: 8dB

Around 10dB power gain is achieved by exploiting the multiuser diversity!

Performance Improvement: BS/AP Allocation

- 4 users / cell
- 128 subcarriers
- BER requirement: $10^{-4}$
- Cell radius: 1km
- Path loss exponent: 4
- Std of log-normal shadowing: 8dB

Outage probability is further reduced by dynamic BS assignment!

Outline

- Introduction to OFDM and MIMO
- Introduction to dynamics in wireless communications systems
- Dynamic resource allocation
  - SISO-OFDM systems
  - MIMO-OFDM systems
- Cross-layer design and optimization
  - Joint MAC-PHY resource allocation
  - Joint design of PHY and networking or application layers

Performance Improvement: BS/AP Allocation

- 8 users in 2 cells
- Non-uniform traffic density
- 128 subcarriers
- BER requirement:
  - Cell radius: 1km
  - Path loss exponent: 4
- Std of log-normal shadowing: 8dB

Dynamic BS assignment effectively mitigates the destructive effect of non-uniform traffic density!
Resource Allocation for MIMO-OFDM: Challenges and Opportunities

- Co-channel interference resistance due to MIMO
- Inter-symbol interference resistance due to OFDM
- Time, frequency, and space domain freedom for adaptive resource allocation

- The optimization problem is more complex due to the presence of co-channel interference
- Users can be multiplexed in both frequency and space domains – have to decide which dimension should be occupied by which set of users

Problem Formulation – Power Minimization

\[
\begin{align*}
\text{arg min}_{p_{k_n}} & \quad \sum_{k_n} p_{k_n} \\
\text{Subject to:} & \quad \sum_{k_n} f_{k_n} = R, \quad \forall k
\end{align*}
\]

Nonlinear! Combinatorial!

BER vs. Channel Correlation

- 2 users
- 64 subcarriers
- QPSK Modulation
- \( E_b/N_0 = 5 \) dB
- 2 Tx/user
- 4 Rx

- BER is affected by CCI
- BER performance degrades when the correlation increases
- When the correlation is low, the performance is similar to that of a single user system
Solution – Clustering

• Divide users into clusters according to the mutual correlations
• Highly correlated users are put in one cluster
• The channel correlation between users in different clusters is lower than a threshold

Solution – Clustering

• For the users with low correlation
  – Assume that the mutual interference is perfectly cancelled by multiuser detection techniques
  – Users can share the same channels and transmit as if there were no co-channel users
  – Adaptive resource allocation reduces to single-user rate-and-power adaptation

Solution – Clustering

• For the users with high mutual correlation
  – The assumption of perfect CCI cancellation is not valid
  – CCI degrades the performance
  – Users DO NOT share sub-channels to avoid CCI

Performance

• 2 users
• 64 subcarriers
• 128 bits/OFDM/user
• 2 Tx/user
• 4 Rx
• PIC detector
• Threshold: 0.6

• Significant performance improvement and diversity gain
• No need to sacrifice antenna diversity in the presence multiple users
Outline

- Introduction to OFDM and MIMO
- Introduction to dynamics in wireless communications systems
- Dynamic resource allocation
  - SISO-OFDM systems
  - MIMO-OFDM systems
- Cross-layer design and optimization
  - Joint MAC-PHY resource allocation
  - Joint design of PHY and networking or application layers

Challenges and Opportunities

- Opportunistic resource allocation that assumes a saturated traffic condition is not accurate in packet-switched networks
  - Resource may be allocated to users that do not have enough packets to transmit
- Resource allocation affects the effective channel capacity seen by the upper layers, and hence has an impact on scheduling
- Multi-user diversity gain, statistical multiplexing gain, time- and frequency-domain diversity
- Key issue: joint optimization of scheduling and subcarrier-bit-power allocation in OFDM networks

System Diagram

- Jointly design Scheduling, Multiple access, Power distribution
- Exclusive subcarrier allocation: $\sum_{i=1}^{n} g_i \leq 1 \ \forall n$
- Number of subcarriers needed by one user: $\sum_{i=1}^{n} g_i = \frac{L}{r} \ \forall k$
  - $g_i$: the number of packets scheduled for user $k$
  - $L$: packet size
  - $r$: data rate on each subcarrier

Constraints – power allocation

➢ To maintain a sufficiently low error rate at the receiver
➢ To smooth the fluctuation in the wireless channel capacity

\[ \sum_{n=1}^{N} \sum_{k=1}^{B} \frac{p_{nk}}{\gamma_k} = \gamma_k \forall n,k \]

\( \gamma_k \): SNR required by user k for achieving a given bit error rate

Constraints – Scheduling

➢ To ensure QoS and fairness from the MAC’s viewpoint
➢ Serve packets in a way that approximates a fair queueing scheme in an error-free system (i.e., a reference scheme)
➢ Explicitly control the leading or lagging of the flows compared to the reference scheme

\[ |Q_k - Q_r| \leq \eta_k \forall k \]

\( Q_k \): queue length of user k
\( Q_r \): queue length of user k in the reference system
\( \eta_k \): maximum allowable leading or lagging

Problem Formulation

\[ \arg \min \sum_{n=1}^{N} \sum_{k=1}^{B} p_{nk} \gamma_k \]

To maintain the received SNR:

\[ \sum_{n=1}^{N} \sum_{k=1}^{B} \frac{p_{nk}}{\gamma_k} = \gamma_k \forall n,k \]

To control leading or lagging:

\[ |Q_k - Q_r| \leq \eta_k \forall k \]

Exclusive subcarrier allocation:

\[ \sum_{n=1}^{N} \gamma_n \leq 1 \forall n \]

Number of subcarriers needed by a user:

\[ \sum_{n=1}^{N} \gamma_n - \frac{1}{\gamma_k} \forall k \]

Maximum number of packets transmitted during a frame:

\[ \sum_{n=1}^{N} g_n = \min \left( \sum_{n=1}^{N} Q_n \frac{N}{L} \right) \]

Performance

• The proposed joint MAC-PHY resource allocation algorithm can achieve
  ➢ Throughput guarantee
    • The throughput of the proposed system is almost the same as that of a fair queueing system with error-free channels
  ➢ Delay guarantee
    • The worst case delay of the proposed system is bounded
  ➢ Fairness guarantee
    • Short-term and long-term fairness is guaranteed at a similar degree as the reference system
  ➢ Significantly higher power efficiency
Performance: Power efficiency

- OFDM symbol duration: 2us
- 256 Subcarriers
- 12 users
- Source rate: 100kbps/user
- QPSK modulation

About 10dB less power is needed in order for the system to be stable.

Outline

- Introduction to OFDM and MIMO
- Introduction to dynamics in wireless communications systems
- Dynamic resource allocation
  - SISO-OFDM systems
  - MIMO-OFDM systems
- Cross-layer design and optimization
  - Joint MAC-PHY resource allocation
  - Cross-layer design in wireless networking

Potential Research Topics

- Joint PHY, MAC, and Networking layer design
  - Joint TCP congestion control and per-link power adaptation
  - Joint routing, scheduling, and power control
  - Adaption admission control
  - Joint optimization of Transport layer retransmission limit, MAC layer retransmission limit, and PHY layer adaptation
- Joint PHY and application layer design
  - Co-design of source coding parameters and MAC-PHY layer resource allocation

Cross-Layer Design – more to come
Conclusion

• Dynamic resource allocation and cross-layer design are emerging technologies that are nowadays under active research throughout the world.
• This talk gave an overview of dynamic multiuser resource allocation.
• It discussed a broad spectrum of important topics, including:
  – Issues and principles of resource allocation in single- and multi-antenna OFDM networks, with or without perfect channel state information.

References