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Dynamic Multiuser Resource Allocation and Adaptation for Wireless Systems

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HKUST
1

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HKUST
2

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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

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3

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ECE Department: State-of-the Facilities

HKUST
4

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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

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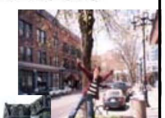
Overseas Exchange Program

- 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
  - École 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., Nanjing U.

PENN
Berkeley



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ECE -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*)

Country	No. Fellows
Australia	35
Taiwan	35
Hong Kong	28
India	26
China	23
Korea	16
New Zealand	3

- ECE Department at HKUST has 11 IEEE Fellows as of December 2006

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(The *Times* of London
Nov 5, 2004)

WORLD'S TOP 50 UNIVERSITIES

1	Harvard University (US)	1,000 pts
2	University of California, Berkeley (US)	880.2
3	Massachusetts Institute of Technology (US)	788.9
4	California Institute of Technology (US)	738.9
5	Oxford University (UK)	731.8
6	Cambridge University (UK)	731.8
7	Stanford University (US)	688.0
8	Yale University (US)	582.8
9	Princeton University (US)	557.5
10	ETH Zurich (Switzerland)	553.7
11	London School of Economics (UK)	484.4
12	Tokyo University (Japan)	482.0
13	University of Chicago (US)	444.0
14	Imperial College London (UK)	443.7
15	University of Texas at Austin (US)	421.5
16	Australian National University (Australia)	417.7
17	Beijing University (China)	391.8
18	National University of Singapore	385.9
19	Columbia University (US)	384.1
20	University of California, San Francisco (US)	376.5
21	McGill University (Canada)	364.1
22	Melbourne University (Australia)	353.2
23	Cornell University (US)	348.8
24	University of California, San Diego (US)	331.5
25	Johns Hopkins University (US)	330.8
26	University of California, Los Angeles (US)	316.4
27	École Polytechnique (France)	315.5
28	Pennsylvania University (US)	306.9
29	Kyoto University (Japan)	303.7
30	École Normale Supérieure (France)	298.4
31	Michigan University (US)	293.3
32	École Polytechnique Fédérale de Lausanne (Switzerland)	289.4
33	Monash University (Australia)	286.0
34	University College London (UK)	284.2
35	Illinois University (US)	281.6
36	New South Wales University (Australia)	275.7
37	Toronto University (Canada)	272.5
38	Carnegie Mellon University (US)	259.4
39	Hong Kong University (Hong Kong)	249.5
40	Sydney University (Australia)	245.2
41	Indian Institute of Technology (India)	241.7
42	Hong Kong University of Sci & Tech (Hong Kong)	240.6
43	Manchester University (UK)	238.5
44	School of Oriental and African Studies (UK)	235.8
45	Massachusetts University (US)	235.7
46	University of British Columbia (Canada)	230.4
47	Heidelberg University (Germany)	228.3
48	Edinburgh University (UK)	227.6
49	Queensland University (Australia)	223.9
50	Nanyang University (Singapore)	217.1

Bristol University: No 91

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2006 Top Universities

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**.

(The Times Higher Education Suppl - Oct. 17, 2006)

Rank	Institution	Country
1	Massachusetts Institute of Technology	US
2	University of California, Berkeley	US
3	Indian Institutes of Technology	India
4	Imperial College London	UK
5	Stanford University	US
6	Cambridge University	UK
7	Tokyo University	Japan
8	National University of Singapore	Singapore
9	California Institute of Technology	US
10	Carnegie Mellon University	US
11	Oxford University	UK
12	ETH Zurich	Switzerland
13	Delft University of Technology	Netherlands
14	Tsing Hua University	China
15	Nanyang Technological University	Singapore
16	Melbourne University	Australia
17	Hong Kong University of Sci & Technol	Hong Kong
18	Tokyo Institute of Technology	Japan
19	New South Wales University	Australia
20	Beijing University	China

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Newsweek International Edition

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.**

(NEWSWEEK International - Aug 13, 2005)

1. Harvard University
2. Stanford University
3. Yale University
4. California Institute of Technology
5. University of California at Berkeley
6. University of Cambridge
7. Massachusetts Institute Technology
8. Oxford University
9. University of California at San Francisco
10. Columbia University

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59. University of California at Santa Barbara
60. Hong Kong University of Science and Techn.
61. Wageningen University
62. Michigan State University
63. University of Munich
64. University of New South Wales
65. Boston University
66. Vanderbilt University
67. University of Rochester
68. Tohoku University
69. University of Hong Kong

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96. Chinese University of Hong Kong
97. University of Newcastle
98. Innsbruck University
99. University of Massachusetts at Amherst
100. Sussex University

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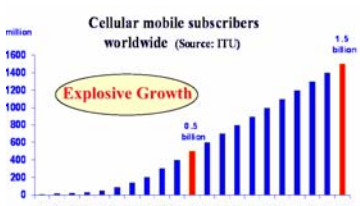
Motivation and Background



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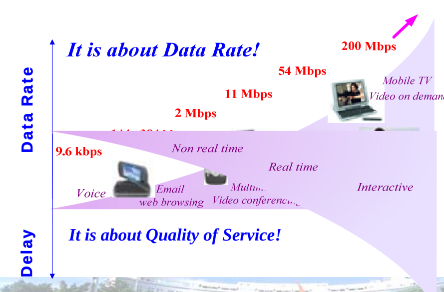
Motivation and Background

It is not just about data rate!



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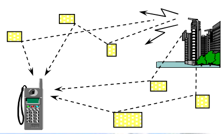
Challenges

- ❑ 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



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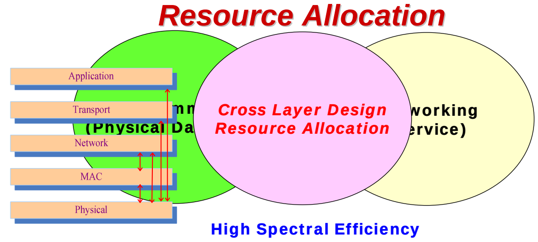
Cross-layer Optimization and Resource Allocation



High Spectral Efficiency

High Energy Efficiency

Overall good performance

K. B. Letaief and Y. J. Zhang, "Dynamic Multiuser Resource Allocation and Adaptation for Wireless Systems," (Invited Paper) IEEE Wireless Commun., Aug. 2006

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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

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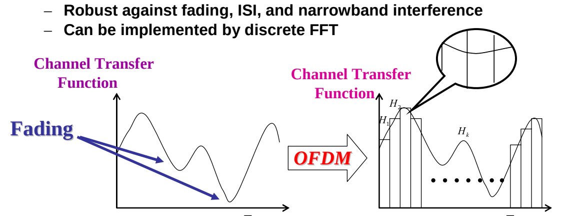
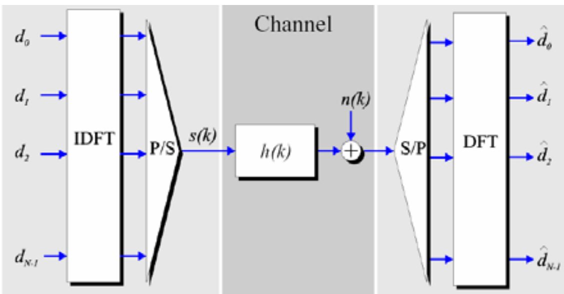
OFDM

- 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



OFDM



MIMO

- Higher transmission rate (multiplexing gain)
- Higher link reliability (diversity gain)
- Wider coverage
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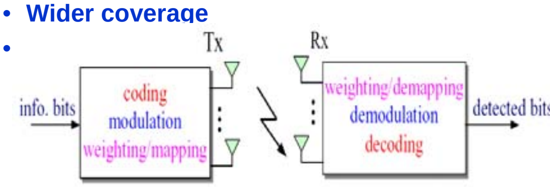
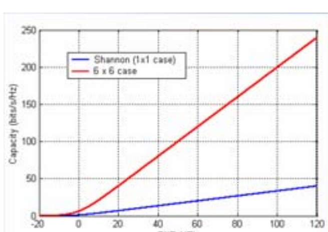


MIMO

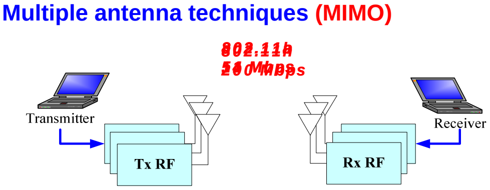
- Capacity of MIMO channel increases linearly with the number of antennas at both sides

$$C = N \log_2\left(1+\frac{P}{\sigma^2}\right)$$



Applications of MIMO and OFDM in WLAN

- Orthogonal frequency division multiplexing (OFDM)
- Multiple antenna techniques (MIMO)



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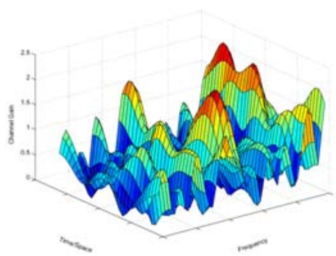
Dynamics in Wireless Communications Systems – Channel Variation

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



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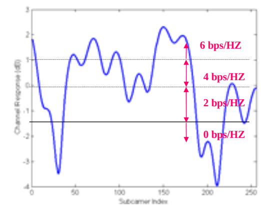
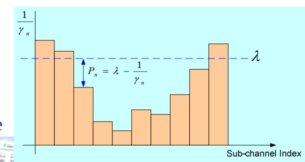
Link Adaptation

- Adaptive modulation
  - Data rate: $\log_2(1+\gamma_n P_n)$
  - γ_n: Effective channel gain on subchannel *n*
  - P_n: Transmit power on subchannel *n*



- Optimal power allocation: *Water filling*

$$P_n = \begin{cases} \lambda - \dfrac{1}{\gamma_n} & \lambda \geq \dfrac{1}{\gamma_n} \\ 0 & \text{otherwise} \end{cases}$$



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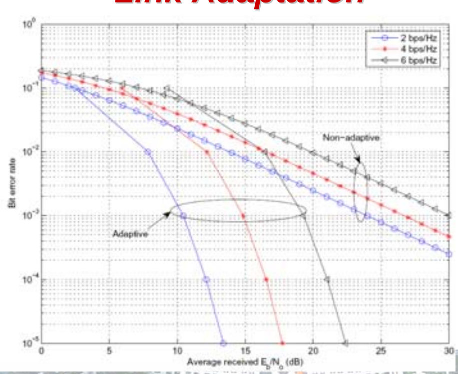
Link Adaptation



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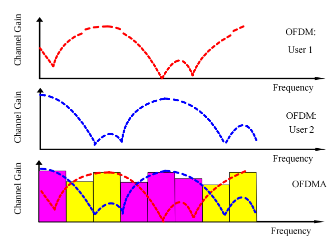
Dynamics in Wireless Communications Systems – Multiuser Diversity

- 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



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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?

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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

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Resource Allocation in SISO-OFDM Systems

- **Resource**: time slots, subcarriers, power
- **Constraints**: Bit error rate, maximum transmit power, minimum data rate, …
- **Objectives**: Maximize spectrum efficiency, power efficiency, or system utility

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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

$$p_{k,n} = \frac{f_k(r_{k,n})}{|h_{k,n}|^2} \text{ for } k, n$$

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Problem Formulation

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

$$\max_{p_{k,n}, c_{k,n}, r_{k,n}} \sum_{n=1}^{N}\sum_{k=1}^{K} c_{k,n} r_{k,n}$$

Subject to: $\sum_{n=1}^{N}\sum_{k=1}^{K} c_{k,n} p_{k,n} \le P_{total}$

$$\sum_{k}^{K} c_{k,n} = 1 \text{ for all } n$$

$$c_{k,n} \in \{0,1\}$$

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Problem Formulation

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

$$\min_{r_{k,n}, p_{k,n}, c_{k,n}} \sum_{n=1}^{N}\sum_{k=1}^{K} c_{k,n} p_{k,n}$$

Subject to: $\sum_{n=1}^{N} c_{k,n} r_{k,n} \ge R_k \text{ for all } k$

$$\sum_{k}^{K} c_{k,n} = 1 \text{ for all } n$$

$$c_{k,n} \in \{0,1\}$$

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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

Y. J. Zhang and **K. B. Letaief**, “Multiuser adaptive subcarrier-and-bit allocation with adaptive cell selection for OFDM systems,” *IEEE Transactions on Wireless Communications*, Sept. 2004.

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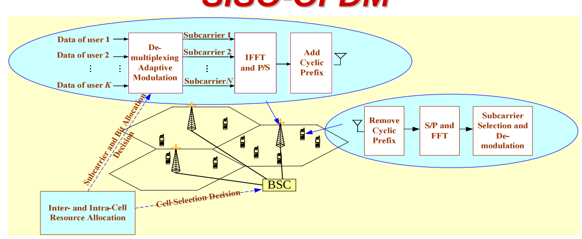
Intra- and Inter-cell Adaptation for SISO-OFDM



- 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

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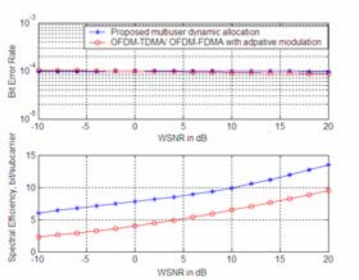
Performance Improvement: Subcarrier-and-Bit Allocation



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

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

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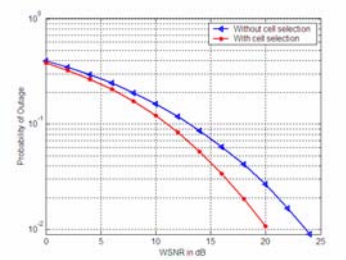
Performance Improvement: BS/AP Allocation



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

Outage probability is further reduced by dynamic BS assignment!

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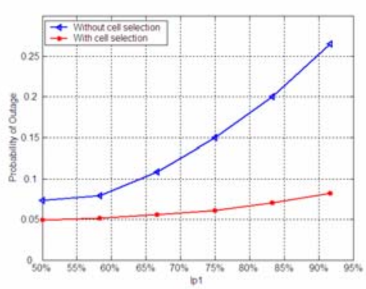
Performance Improvement: BS/AP Allocation



- 8 users in 2 cells
- Non-uniform traffic density
- 128 subcarriers
- BER requirement:
- Cell radius: 1*km* 10^{-4}
- Path loss exponent: 4
- Std of log-normal shadowing: 8dB

Dynamic BS assignment effectively mitigates the destructive effect of non-uniform traffic density !

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- Introduction to OFDM and MIMO
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- **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

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

$$\arg\min_{p_{k,n}, r_{k,n}} p_{tot} = \sum_{k=1}^{K}\sum_{n=1}^{N} p_{k,n}$$

Subject to:

$$\sum_{n=1}^{N} r_{k,n} = R_k \ \forall k$$

$$p_{k,n} \geq 0$$

$$r_{k,n} \geq 0$$

$$p_{k,n} = f\left(BER_{targ}, r_{k,n}, g_{k,n}\right)$$

QoS Constraints

Nonlinear!

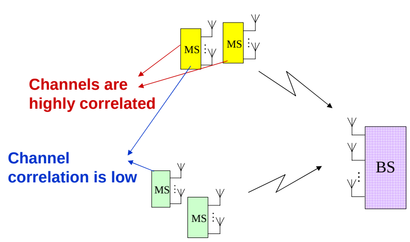
Combinatorial!

Carrier to interference and noise ratio

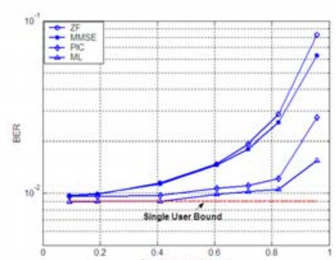
$$g_{k,n} = g(\{h_{k',n}\}_{k'=1,\cdots K}, \{p_{k',n}\}_{k=1,\cdots,k-1,k+1,\cdots,K})$$

Y. J. Zhang and K. B. Letaief, “An efficient resource allocation scheme for spatial multiuser access in MIMO/OFDM systems,” IEEE Transactions on Communications, Jan. 2005

Solution – Clustering



BER vs. Channel Correlation



- 2 users
- 64 subcarriers
- QPSK Modulation
- *Eb*/*No*: 5dB
- 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

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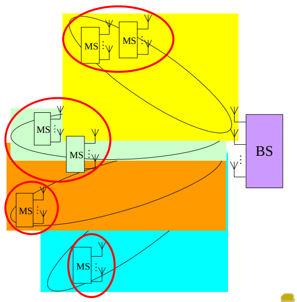
Solution – Clustering

- 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



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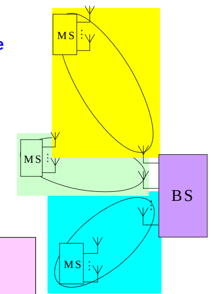
Solution – Clustering

- 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



$$\arg\min_{p_{k,n},r_{k,n}} \sum_{n=1}^{N} p_{k,n}$$

$$\sum_{n=1}^{N} r_{k,n} = R_k$$

$$p_{k,n} = f\left(BER_{t\arg}, r_{k,n}, \left|\frac{(h_{k,n})^2}{\sigma^2}\right| \right)$$

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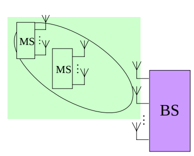
Solution – Clustering

- 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



$$\arg\min_{p_{k,n},r_{k,n},c_{k,n}} p_{tot} = \sum_{k=1}^{K}\sum_{n=1}^{N} p_{k,n}c_{k,n}$$

$$\sum_{n=1}^{N} r_{k,n}c_{k,n} = R_k \ \forall k$$

$$\text{if } c_{k,n} = 1, \text{ then } c_{k',n} = 0 \ \forall k' \neq k$$

$$p_{k,n} = f(BER_{t\arg}, r_{k,n}, h_{k,n})$$

No longer combinatorial!

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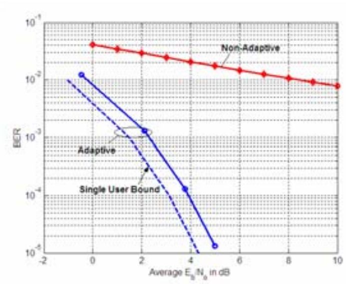
Performance



- 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

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  - MIMO-OFDM systems
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  - Joint design of PHY and networking or application layers

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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

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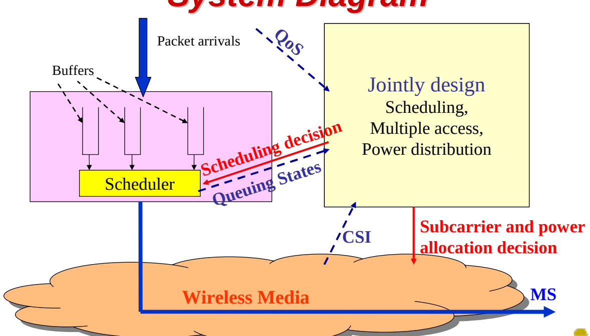
System Diagram



Y. J. Zhang and K. B. Letaief, "Cross layer adaptive resource management for wireless packet networks with OFDM signaling," *IEEE Transactions on Wireless Communications*, Nov. 2006

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Constraints – subcarrier allocation

- Allocate subcarriers to the packets that are scheduled for transmission
- Allocate subcarriers in a most power efficient way

Exclusive subcarrier allocation: $\sum_{k=1}^{K} c_{k,n} \le 1 \;\; \forall n$

Number of subcarriers needed by one user: $\sum_{n=1}^{N} c_{k,n} = g_k \frac{L}{r} \;\; \forall k$

g_k: the number of packets scheduled for user k

L: packet size

r: data rate on each subcarrier

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Constraints – power allocation

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

$$\frac{|h_{k,n}|^2 p_{k,n}}{N_o B} = \gamma_k \quad \forall n,k$$

γ_k: SNR required by user k for achieving a given bit error rate

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Constraints – Scheduling

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

$$|Q_k - Q_k^r| \le \eta_k \quad \forall k$$

Q_k: queue length of user k

Q^r_k: queue length of user k in the reference system

η_k: maximum allowable leading or lagging

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Problem Formulation

$$\arg\min_{p_{k,n},c_{k,n},g_k} \sum_{k=1}^{K}\sum_{n=1}^{N} p_{k,n} c_{k,n}$$

To maintain the received SNR:	$\frac{\lvert h_{k,n}\rvert^2 p_{k,n}}{N_o B} = \gamma_k \quad \forall n,k$
To control leading or lagging:	$\lvert Q_k - Q_k^r\rvert \le \eta_k \quad \forall k$
Exclusive subcarrier allocation:	$\sum_{k=1}^{K} c_{k,n} \le 1 \; \forall n$
Number of subcarriers needed by a user:	$\sum_{n=1}^{N} c_{k,n} = g_k \frac{L}{r} \quad \forall k$
Maximum number of packets transmitted during a frame:	$\sum_{k=1}^{K} g_k = \min(\sum_{k=1}^{K} Q_k, \frac{Nr}{L})$

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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 queuing 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

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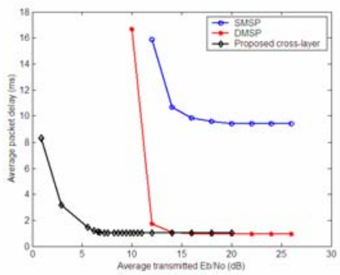
Performance: Power efficiency



- **SMSP**: Static MAC - Static PHY (TDMA, no rate/power adaptation)
- **DMSP**: Dynamic MAC - Static PHY (Statistical multiplexing, no rate/power adaptation)

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

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

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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**

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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
  - Adaptive 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

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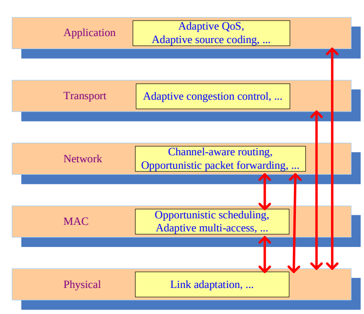
Cross-Layer Design – more to come



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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

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