Wireless Packet Scheduling Algorithms for Single-Cell Networks

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Outline

Opportunistic Scheduling with Generalized Fairness Constraints

There exists a *fundamental* trade-off between system performance and fairness among users in the context of opportunistic scheduling, especially in *heterogeneous* environments

Generalized fairness constraints:

- Temporal fairness
- Utilitarian fairness
- Minimum performance guarantee
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Opportunistic Scheduling with Temporal Fairness: An Example

Notations

- $\mathcal{N}$: the set of users, usually indexed by i
- $\mu_i(t)$: the data rate for user i in time slot t. Thus, $\vec{\mu}(t) = [\mu_1(t), \ldots, \mu_N(t)]$ denotes the data rate vector of all users at time t
- $Q(\vec{\mu}(t))$: a scheduling policy to select a user to serve in time slot t, given $\vec{\mu}(t)$
- $I_{Q(\vec{\mu}(t))=i}$: an indicator function that takes 1 given user i is scheduled at the time slot t and 0 otherwise
- G_i: the time fraction that user i intended to achieve

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$$\max_{Q} \sum_{i \in \mathcal{N}} E\{\mu_i I_{Q(\vec{\mu})=i}\}$$

such that

$$E\{I_{Q(\vec{\mu})=i}\} \geq G_i, \ \forall i \in \mathcal{N}$$

The optimal scheduling policy can be derived by a Lagrange dual argument.

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Considering any feasible policy Q, there exists non-negative constants λ_i such that the following holds

$$
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\sum_{i \in \mathcal{N}} E\{\mu_i I_{Q(\vec{\mu})=i}\} &\leq \sum_{i \in \mathcal{N}} E\{\mu_i I_{Q(\vec{\mu})=i}\} + \sum_{i \in \mathcal{N}} \lambda_i [E\{I_{Q(\vec{\mu})=i}\} - G_i] \\
&= \sum_{i \in \mathcal{N}} E\{\mu_i I_{Q(\vec{\mu})=i} + \lambda_i I_{Q(\vec{\mu})=i}\} - \sum_{i \in \mathcal{N}} \lambda_i G_i \\
&\leq \sum_{i \in \mathcal{N}} E\{(\mu_i + \lambda_i) I_{Q^*(\vec{\mu})=i}\} - \sum_{i \in \mathcal{N}} \lambda_i G_i \\
&= \sum_{i \in \mathcal{N}} E\{\mu_i I_{Q^*(\vec{\mu})=i}\} + \sum_{i \in \mathcal{N}} \lambda_i [E\{\mu_i I_{Q^*(\vec{\mu})=i}\} - G_i] \\
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Opportunistic Scheduling with Temporal Fairness: An Example (cont.)

The optimal scheduling policy is

$$Q^*(t) = \arg\max_i \{\mu_i(t) + \lambda_i\}$$

where $\lambda_i = 0$ if $E\{\mu_i I_{Q(\vec{\mu})=i}\} > G_i$

- The optimal scheduling policy is an *index* rule
- Lagrange multiplier λ_i can be viewed as an "offset"
- λ_i can be calculated by a stochastic approximation algorithm online
- Especially, When setting $\lambda_i = 0 \; \forall i \in \mathcal{N}$ (i.e., $G_i = 0$), the fairness constraint disappear and the scheduling policy rolls back to the greedy one

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Outline

Multiple Interfaces in PHY

Multiple interfaces in PHY

- OFDMA
- MIMO
- MIMO-OFDMA
- ...

Implications of multiple interfaces to the design of scheduling algorithms

- More resources (e.g., sub-carrier, antenna) are available
- More complicated mapping between users and resources (e.g., multiple users are scheduled during one time slot)

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Orthogonal-Frequency-Division-Multiplexing (Access)

OFDM

- Can easily adapt to severe channel conditions without complex equalization
- Robust against narrow-band co-channel interference
- Robust against Inter-symbol interference (ISI) and fading caused by multi-path propagation
- High spectral efficiency
- Efficient implementation using FFT
- Low sensitivity to time synchronization errors

OFDMA: multi-user OFDM

- It schedules *multiple* users during one time slot, exploiting not only *frequency diversity* but also *multi-user diversity*

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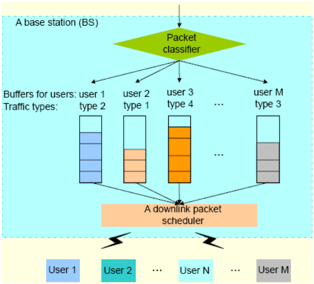
System Model: OFDMA



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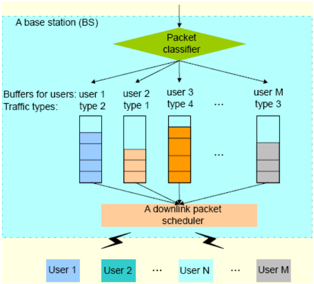

Opportunistic Scheduling in OFDMA with Temporal Fairness: An Example

Notations

- $\mathcal{K}$: the set of sub-carriers, usually indexed by k
- $\mu_i^k(t)$: the data rate for user i by using sub-carrier k at time slot t
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Problem Formulation

$$\max_{Q} \sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{K}} E\{\mu_i^k I_{Q^k(\vec{\mu})=i}\}$$

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$$Q^*(t) = K \arg\max_{i,k}\{\mu_i^k(t) + \lambda_i\}$$

where $\lambda_i = 0$ if $\sum_{k \in \mathcal{K}} E\{\mu_i^k I_{Q^k(\vec{\mu})=i}\} > G_i$

- The optimal scheduling policy is a generalization of an index rule (one-dim ⇒two-dim resource allocation)
- $K \arg\max_{i,k}\{.\}$ is a “Maximum Weight Matching” operator in a bipartite graph (i.e., the set of users and the set of sub carriers)
- Power allocation (e.g., water-filling solution) can further enhance the system performance

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Multiple-Input-Multiple-Output

MIMO

- Increase transmission radius
- Improve transmission reliability
- Increase spectrum efficiency
- Increase scattering, beneficial multi-user diversity

Applications

- Spatial diversity
- Spatial multiplexing
- Space-time coding
- Opportunistic beamforming

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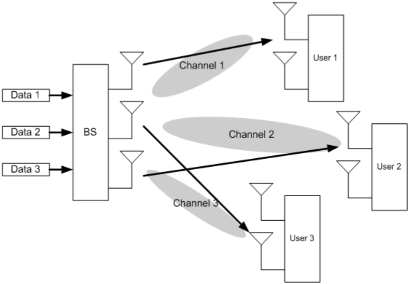

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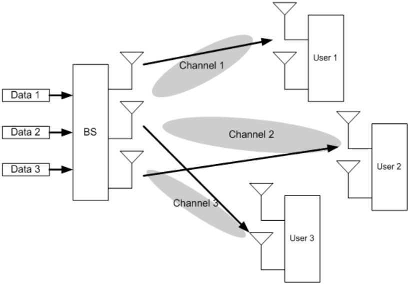

Opportunistic Scheduling in MIMO with Temporal Fairness: An Example (cont.)

Using k to index the transmit antenna at the Base Station, the optimal scheduling policy is

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Multi-Carrier Multi-Antenna Communications

MIMO-OFDMA: MIMO operation over frequency domain (*overlay*)

- Frequent-flat sub-carriers
- Simpler frequency domain equalizer
- Scalable with bandwidth

The scheduling policy in MIMO-OFDMA

- The allocated resource with a finer granularity ((sub-carrier, antenna)) $\Rightarrow$ higher spectrum efficiency
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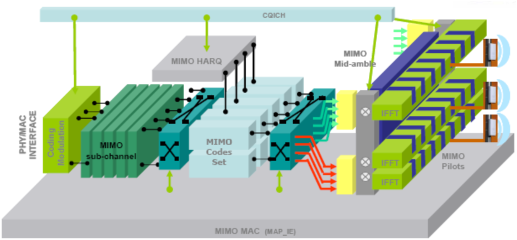

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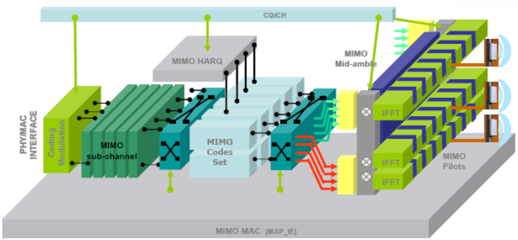

Q & A
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