Cross-layer Scheduling and Resource Allocation in Wireless Communication Systems

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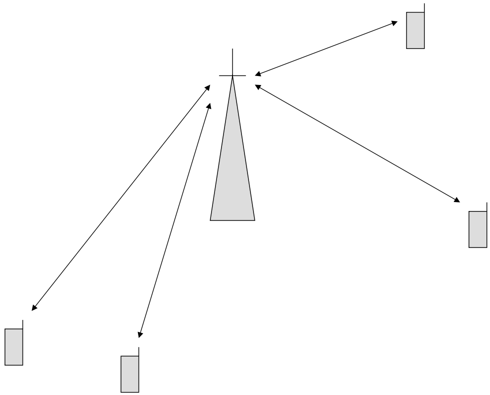
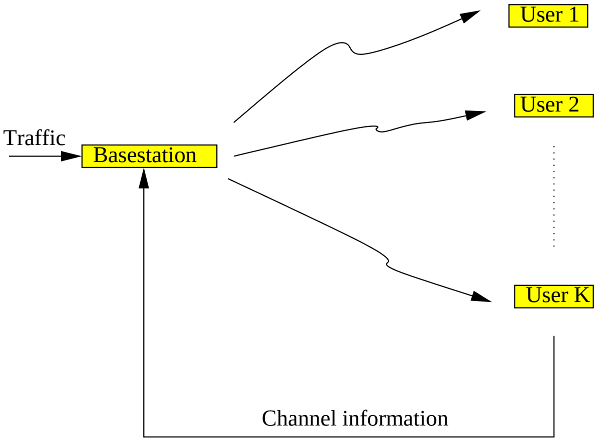
Cellular Systems



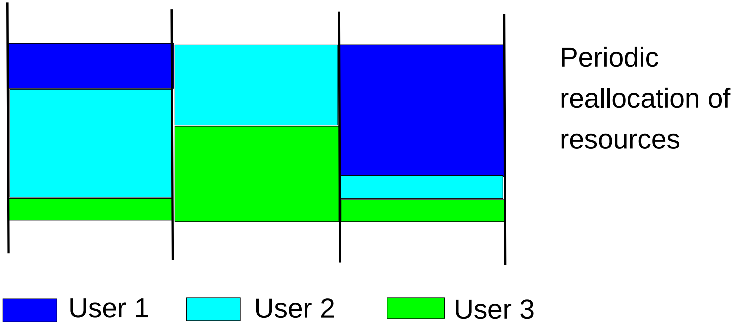
- Time-varying channel
- Resource sharing – Interference constraints

Downlink Resource Allocation Problem



- Physical resources: power and bandwidth
- Total transmit power constraint
- Maximize system throughput
- Fairness or Quality of Service (QoS) constraints

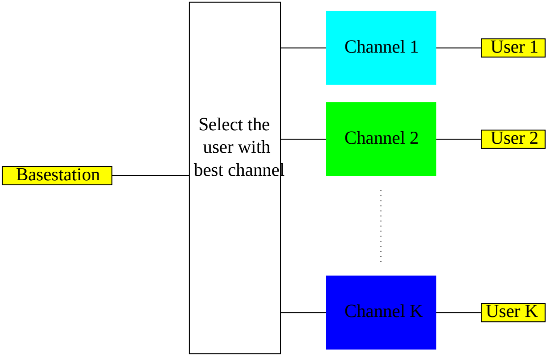
Dynamic Resource Allocation



- Resources: Time, Bandwidth, Power
- Adaptation to channel and traffic conditions
- Dynamic resource allocation
  - Reallocation period of the order of a millisecond

Adapting to the Channel

Adapting to the Channel: Maximizing Capacity

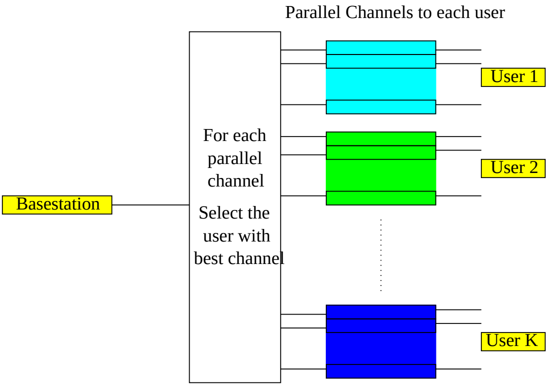


- Infinite backlog assumption
- All power and bandwidth resources to one user
- User with best achievable rate chosen:

$$i = \arg\max_{k} R_k,$$

where R_k is the rate that can be supported by user k.

Maximizing Capacity: Parallel Channels



- Bandwidth resources split to achieve parallel channels
- For each channel n, user with best channel conditions chosen:

$$i_n = \arg\max_k R_{k,n}.$$

- Water-filling power allocation

Fairness

Proportional Fairness

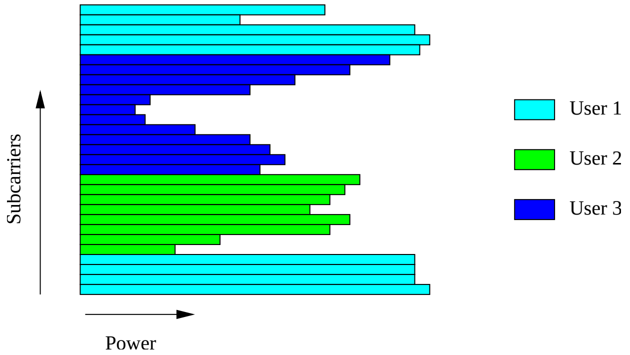
- $i = \arg\max_{k} \frac{R_k}{R_{k,av}}$,

  where $R_{k,av}$ is the average rate that can be supported by user k.

- $\max \sum_k \log(T_k)$,

  where T_k is the average long-term throughput of user k.

Parallel Channels: OFDM

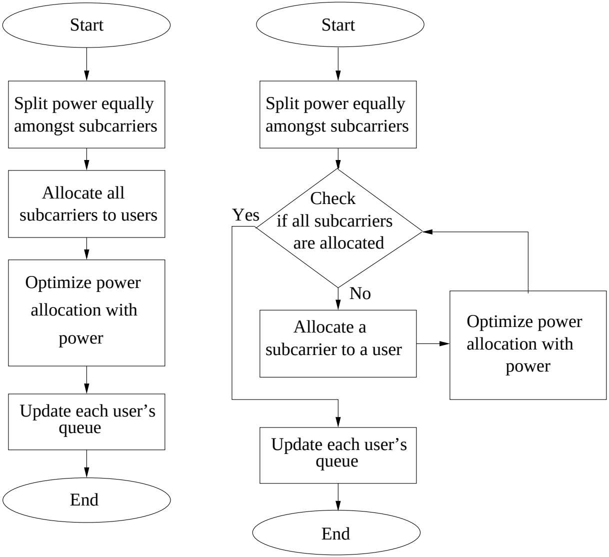


- Available resources:
  - Subcarriers
  - Transmit power
- Channel is frequency-selective $\Rightarrow$ subcarriers not identical.

Fairness: Joint Subchannel and Power Allocation

- Proportional rate subcarrier allocation [Rhee]
- Proportional rate subcarrier allocation + power optimization [Shen]
- Joint subcarrier and power allocation

Fairness: Joint Subchannel and Power Allocation



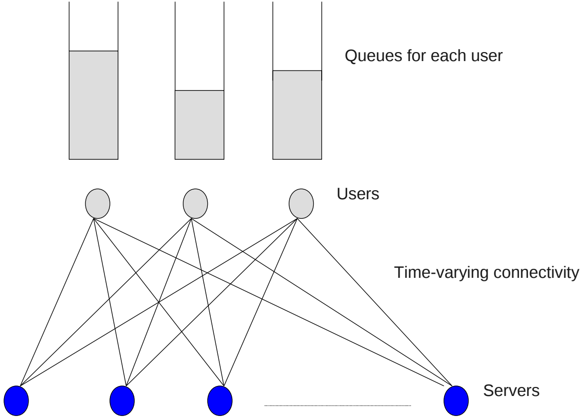
Gradient Algorithm

Stolyar (2005)

- General utility functions
- Multiuser scheduling at the same time
- PF is a special case

Adapting to the Channel and Traffic

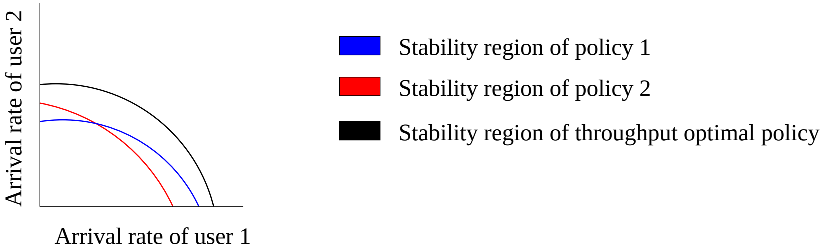
Adapting to the Channel and Traffic



- Multi-Queue Multi-Server Model for each time slot
- Server: Subcarrier/Group of subcarriers/Spreading code

Resource Allocation/Cross-layer Scheduling Goals

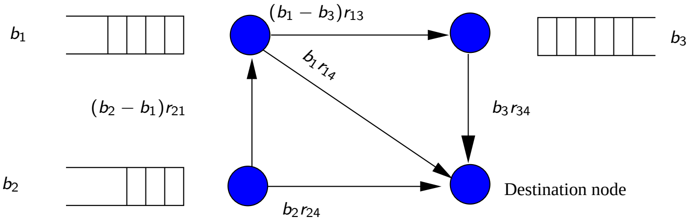
- Scheduling Goals
  - Stability and throughput optimality
    - ★ Stability: Average queue length finite



  - Packet delay constraints
  - Fairness

Stability in a general wireless network

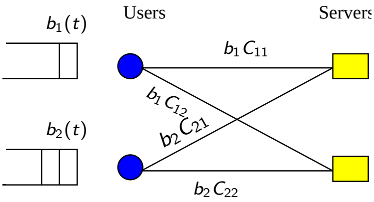
- [Tassiulas et al 1992, Georgiadis et al 2006]
  - Dynamic backpressure policy



- Interference model: Only certain links can be activated simultaneously
- Scheduling problem: Which links will you activate?
- Solution: Activate those links such that the sum of their weights is maximum.

Dynamic back-pressure policy for our setting

Max-Weight Scheduling

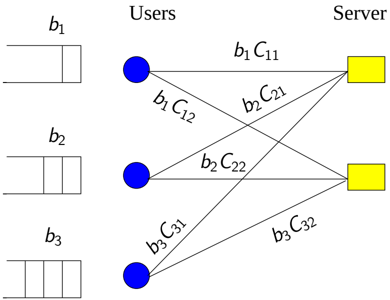


- Only one link per server to be activated. Which links to activate?
- *Solution*:
  - Make the servers as destination nodes.
  - Assign the weights for each link as in back-pressure policy.
  - Activate those links such that the sum of their weights is maximum.

$$\max \sum_k b_n C_{nk}$$

b_n: Backlog of user n, C_{nk}: Capacity of user n on server k

Two Throughput Optimal Policies

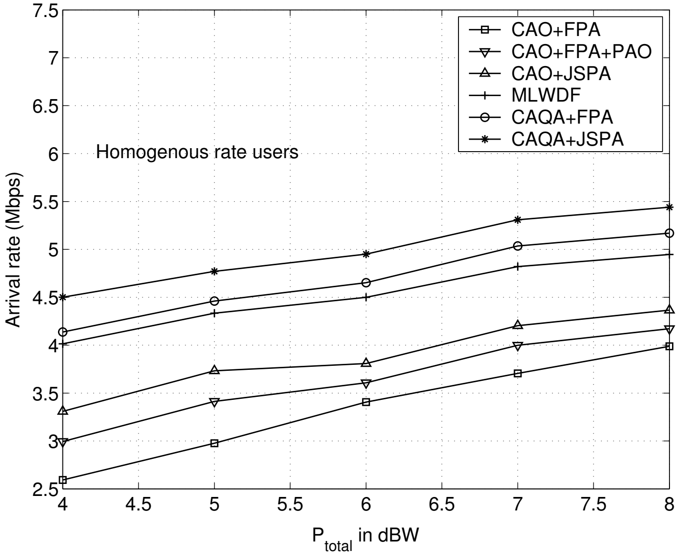


- Policy 1: Max-Weight Scheduling
- Policy 2: Improving delay performance
  - Update queue information after each server is scheduled

Joint Server and Power Allocation

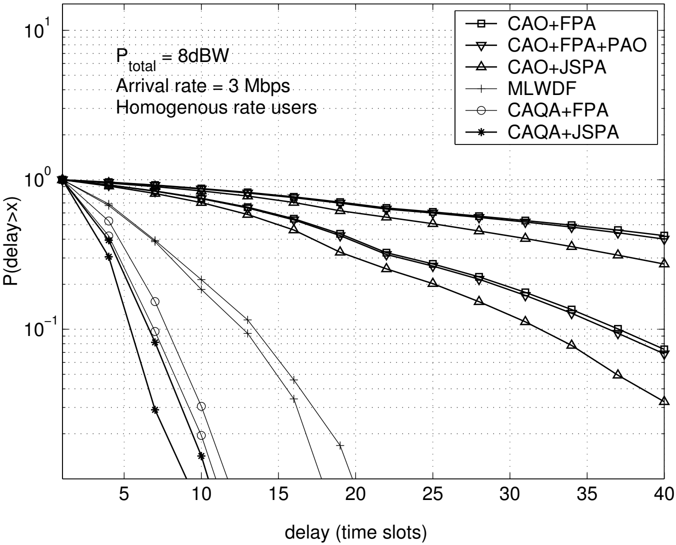
- Finite number of power levels
  - Max-weight scheduling
- Joint subcarrier and power allocation
  - Joint optimization
  - Sub-optimal solutions

Results: Max. Arrival Rate vs. Transmit Power



- Max. arrival rate for less than 0.5% packets dropped

Results: Delay Performance



- Best and worst delay performance among users plotted

Fairness and Utility Maximization

- Arrival rate vector outside stability region
  - Support a fraction of the traffic
  - Optimize utility based on long term throughput
  - Flow control to get stabilizable rates + stabilizing policy
  - Fairness based on choice of utility function
    - ⋆ Proportional fairness

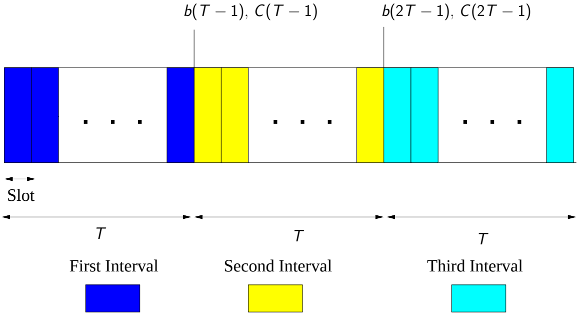
Fairness and Utility Maximization

- Flow control + stabilizing policy
- Maximize utility subject to stability

$$\max_{\{r_k\}} \sum_k [V f_k(r_k) - b_k r_k]$$

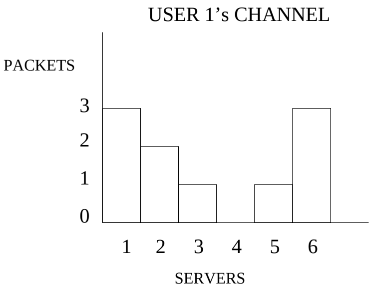
Adapting with Partial Information

Using Delayed Information



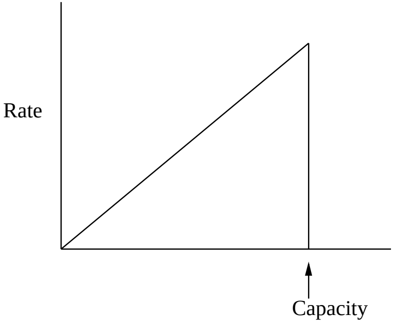
- Time-slots are grouped into intervals
- Channel and queue information available only once in T slots

Channel model



- C_{nk}: channel capacity of user n on server k.
- $C_{nk} \in \{0, 1, 2, 3\}$.

Loss model



Packets sent

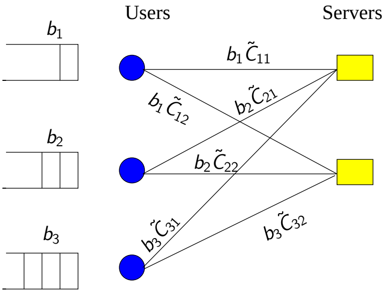
R_{nk}	0
$R_{nk} <= C_{nk}$	$R_{nk} > C_{nk}$

- R_{nk}: number of packets user n transmits on server k.
- $C_{nk}(lT - 1)$: channel information available at the start of l^{th} interval.

Scheduling with infrequent measurements

- Retain throughput optimality of dynamic backpressure policy
- Two policies: Policy 1 and Policy 2
- Comparison with KLS policy [Kar et al 2007]

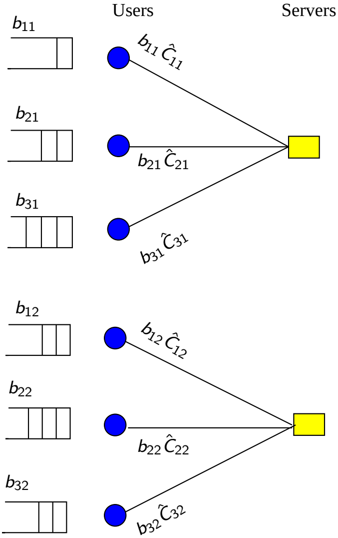
Policy 1 & Policy 2



$$\text{Define} \quad \tilde{C}_{nk} = \max E\left[T_{nk}(t) | C_{nk}(lT-1)\right] = \max_r r \Pr\{r \leq C_{nk} \mid C_{nk}(lT-1)\}$$

- Policy 1 is the dynamic back pressure policy for our setting
- Assignment changes every slot
- Policy 2: Update queue information after each server is scheduled

KLS Policy



- Virtual queue for each user-server pair
- Define $\hat{C}_{nk}(lT)$ as

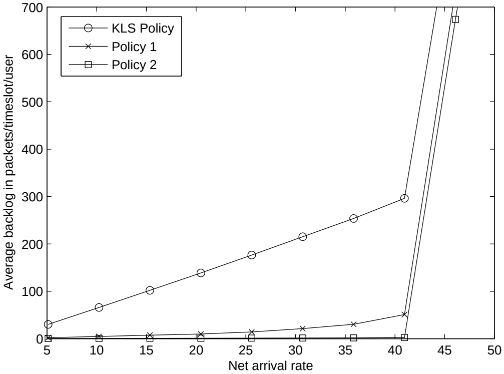
$$\frac{1}{T}\mathbb{E}\left[\sum_{t=lT}^{(l+1)T-1} C_{nk}(t) \middle| C_{nk}(lT-1)\right]$$

- Assignment changes once in T slots

Simulation setup

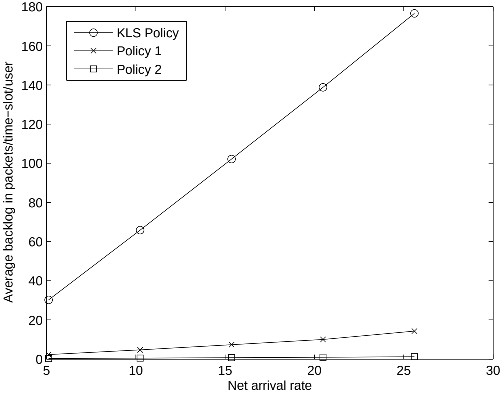
- Truncated Poisson arrivals
- 128 users and 16 servers
- Markov fading channel with probability transition matrix
- Backlog and delay are used as metrics for comparison
- Simulations for both symmetric and asymmetric arrivals
  - Symmetric case shown here

Average backlog comparison: Slow fading, $T = 8$



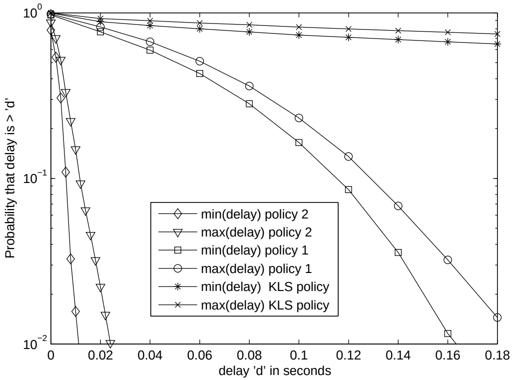
- All the policies have similar stability region.

Average backlog comparison for low traffic



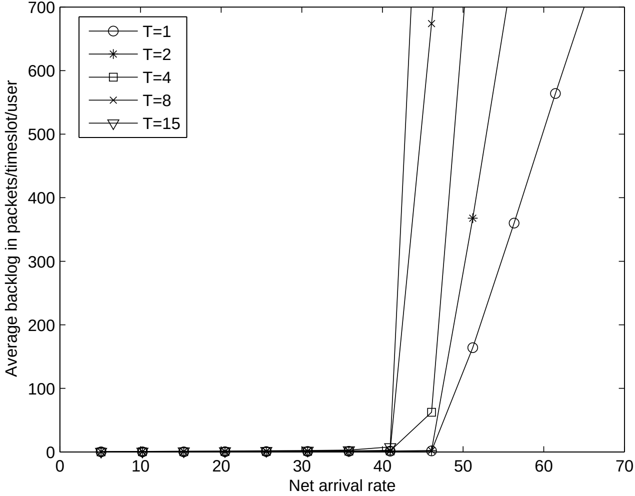
- At low traffic, proposed policies outperform KLS policy.

Delay comparison

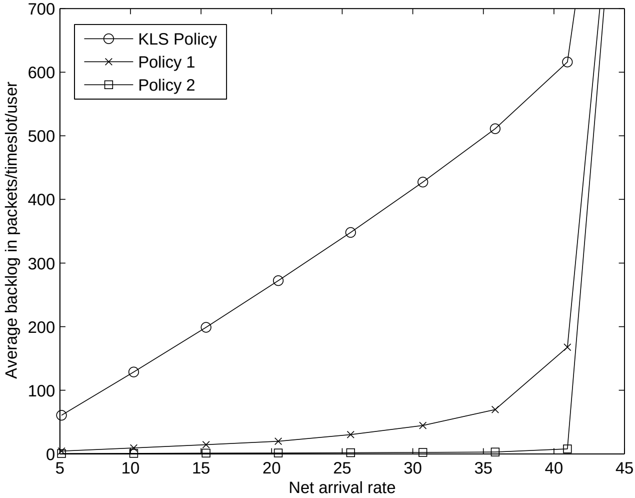


- Net arrival rate $= 25.6$, $T = 4$

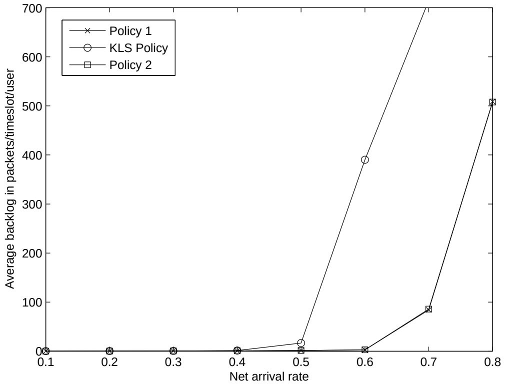
Average backlog comparison vs T for Policy 2



Average backlog comparison for different policies



Comparison of stability regions: Fast fading



- 2 queues, 1 server, $T = 2$, states are $\{0, 1\}$
- Probability transition matrix: $\begin{bmatrix} \delta & 1-\delta \\ 1-\delta & \delta \end{bmatrix}$, $\delta = 0.1$

Possible Extensions

More Physical Layer Options

- Multiple antennas
- Power allocation across resources (servers)
- Interference processing vs. Interference avoidance
- Multi-cell scenario: Centralized vs. Distributed methods

Approximate Solutions

- Lower complexity/approximate solutions to optimization problem
- Appropriate reduction search space of physical layer modes

Summary

- Adapting to the channel
- Adapting to the channel and traffic
  - Max-weight Scheduling
- Adapting to partial information
  - Conditional expected rate
- Possible extensions
  - Approximate lower complexity solutions
  - Appropriate choice of physical layer modes

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