QoS and Resource Allocation in Wireless Networks

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Indo-US Symposium on Frontiers of Engineering
March 01-03, 2006

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   - Energy Efficient Resource Allocation for Single User case
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QoS

- QoS Attributes
  - Throughput
  - Delay and Delay Jitter
  - Loss
  - Fairness
- QoS Classes
  - CBR
    - Constant bandwidth allocation
  - Real time VBR
    - Bound on Maximum delay
    - Specific bandwidth requirement
  - Non real time VBR
    - Minimum bandwidth allocation
  - ABR
    - Available bandwidth is allocated.

QoS Components

- Admission Control
- Packet Scheduling
- Mobility Management

We focus on packet scheduling in wireless networks

Fair Scheduling in Wireline Networks

- Frame based scheduling
  - Time is split into frames.
  - Reservations are made in terms of the maximum amount of traffic that the session is allowed to transmit during a frame.
- Sorted priority based scheduling
  - Global variable is associated with link being scheduled.
  - It is updated on packet arrival/departure.
  - Packet is time stamped with a value which is a function of this variable.
  - Packets are sorted based on their timestamps.

Fluid Flow Fair Queuing (FFQ)[1]

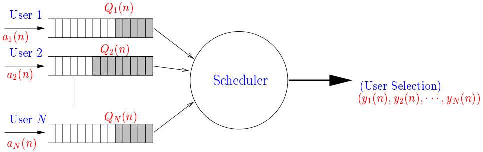

Figure: Scheduler Model

- Traffic is considered fluid.
- FFQ serves each backlogged flow at every instant with a minimum rate equal to its reserved rate.
- Excess bandwidth is distributed among backlogged flows in proportion to their reservations.
- Wighted Fair Queuing(WFQ), a packetized version of FFQ.

Challenges in Wireless Networks

- Channel errors are location dependent and bursty.
- Channel is time varying.
- Mobile host- limited battery life.
- Mobility introduces problem for time stamping.

Wireless Fair Scheduler Components

- An error free service model.
  - Service to session with error free channel.
- Lead/Lag counter
  - Indicates lead/lag of the service with respect to error free model.
- Compensation model
  - Lagging sessions may be compensated.
- Monitoring and predicting the channel state.

Fair Scheduling for Wireless Networks [2] [3],[4]

- Idealized Wireless Fair Queuing
  - Error free service simulated by WFQ.
  - Lagging flow have lowest service tag values.
  - Bounds are set in the lead/lag value.
- Channel Condition Independent fair Queuing
  - A parameter α is used to control the rate at which leading session gives up its lead.
- Server Based Fairness approach
  - Reserves a fraction of bandwidth for compensation.
  - Uses reserved bandwidth for compensation rather than swapping.

Scheduling Algorithms for 802.11 based WLAN [5], [6]

- 802.11 based on CSMA/CA.
- The collision avoidance
  - Inter Frame Space (IFS)
    - Wait time for MS after it senses the idle channel and enters the transmission.
  - Back-off algorithm
    - If the channel is busy, a back-off interval is randomly selected between minimum and maximum contention window (CW_{min}, CW_{max}).

Fair Scheduling in 802.11 WLAN

- Distributed Weighted Fair Queuing
  - All flows of all MS's are constrained to have the same ratio $L_i = \frac{R_i}{W_i}$, where R_i is the thoughput and W_i is the weight for user i.
  - WFQ algorithm is used for scheduling.
- Distributed Deficit Round Robin
  - Based on the concept of DRR.
  - Deficit counter
    - accumulated quanta
  - Deficit counter value is mapped to appropriate IFS value.
  - A large deficit counter results in smaller IFS value.

Cross Layer Approach for Scheduling

- Channel varies with time randomly and asynchronously for different users.
  - Due to different interference levels.
  - Due to fast fading.
- Need to develop resource allocation by taking into account physical channel characteristics.

System Model

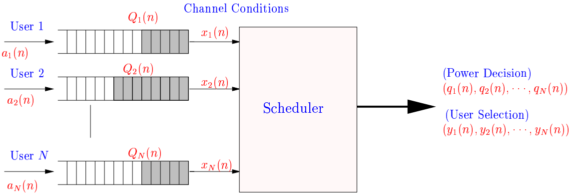

Figure: Single hop system model

We assume

- Cellular slotted TDMA system.
- Users connect to a base station to receive and transmit *data*.
- Scheduler has perfect channel state information

Thoughput Optimal Scheduling (Andrews et al)

- A scheduling algorithm is throughput optimal if it is able to keep 'queues' stable (if it is feasible).
- $D_j(t)$= Head of line packet delay for queue j.
  $r_j(t)$=channel capacity for flow j.
- Scheduling rule is thoughput optimal-
  - Schedule the user for which $\gamma_j D_j(t) r_j(t)$ is maximum.
  - γ_j is some constant.
- Choice of γ_j can control packet delay distribution for different users.
- This is called "Modified Largest Weighted Delay First" algorithm.

Delay Constrained Packet Scheduling-Our Approach

- Design a scheduler that maximizes the throughput.
- The scheduler satisfies the delay guarantees.

Formulation as an Optimization Problem
Variables

Let

- $y_i(n)$ be an indicator variable for user i in time slot n.
- $a_i(n)$ number of arrivals for user i in time slot n.
- $r_i(n)$ be the rate for user i in time slot n.
- $Q_i(n)$ be the queue length for user i in time slot n.
- Let there be N users in the system.

We want to maximize the average throughput given by,

$$T_{av}(N,\overline{D}) = \liminf_{M\to\infty} \frac{1}{M}\sum_{n=1}^{M}\sum_{i=1}^{N} y_i(n)r_i(n) \tag{1}$$

Formulation as an Optimization Problem

Constraints

- Using Little's law, we convert the delay constraints $\overline{D}$ into queue length constraints $\overline{Q}$.

We want to satisfy the constraints given by,

$$\limsup_{M \to \infty} \frac{1}{M} \sum_{n=1}^{M} Q_i(n) \leq \overline{Q}_i \quad i = 1, \ldots, N \tag{2}$$

Formulation as an Optimization Problem
The unconstrained problem

- Introduce Lagrange Multipliers (LMs), hence the problem becomes, maximize $L(\pi, \lambda)$, given by,

$$L(\pi, \lambda) = \liminf_{M \to \infty} \frac{1}{M} \sum_{n=1}^{M} \sum_{i=1}^{N} [y_i(n) r_i(n) - \lambda_i Q_i(n)] \quad (3)$$

  where π is the policy.
- The objective is to find the *saddle* point of this Lagrangian function.
- π forms the primal variable while λ forms the dual variable.
- We use primal-dual approaches for solving the problem.

Solution Methodologies

- The problem stated above is a Markov Decision Problem.
- Finding the optimal policy using value iteration has very high computational complexity.
- We suggest heuristic policies to solve the problem.

Heuristic Policy

- Intuitively, some weighted combination of queue length and channel rate should decide the user who is scheduled.
- We suggest policies of the type, Schedule a user j such that

$$j = \arg\max_i \{Q_i + \theta_i r_i\} \quad (4)$$

An approach based on parameterized policy iterations

- We try to find out the best policy from within a subset of policies described by a parameter θ.
- The transition probabilities and reward functions are dependent on parameter θ.
- Start with an initial policy based on some initial value of θ.
- Improve the policy by improving the value of θ in the direction of gradient of the reward function.
- At the same time, adjust the LMs so that the resultant policy is constraint satisfying.

Energy Efficiency

- Energy efficiency is a primary concern dealing with wireless devices.
- Two approaches for saving energy
  - Convex Power-rate relationship
    - Choose the rate at various stages in transmission in appropriate fashion.
  - Time varying nature of channel
    - defer transmission of packets during “bad” channel to “good” channel state.
- Leads to energy-delay trade off.

Optimal Resource Allocation for Single User Case

- The queue length dynamics is given in terms of packet departure r_n and arrivals a_n.

$$Q_{n+1} = Q_n - r_n + a_{n+1}$$

- Average Delay

$$D = \limsup_{M\to\infty} \frac{1}{M}\mathbf{E}\left[\sum_{n=1}^{M} Q_n\right]$$

- Average Power

$$P = \limsup_{M\to\infty} \frac{1}{M}\mathbf{E}\left[\sum_{n=1}^{M} x_n \mathbf{E}(r_n)\right]$$

where x_n denotes the channel fade process.

- Determine a scheduling policy that minimizes P subject to a constraint on D .

Optimal Policy Characterization (Berry-Gallager)

- Trade-off between average delay and average power for transmission.
- Trade-off is studied in the region of asymptotically large delays for i.i.d. channel and arrival process. Few results to state are:
  - $P - D$ region achieved by all the possible schedulers is a convex region.
  - $P^*(D)$ is a non increasing convex function of D.
  - Average power with average transmission rate constraint approaches to delay optimal power as $\Theta(\frac{1}{D^2})$, asymptotically as $D \rightarrow \infty$.

Optimal Policy Structural results -Our Work

- For Markov packet arrival process and i.i.d. channel fade, optimal stationary policy is
  - increasing in buffer occupancy.
  - increasing in number of packet arrivals in previous slot.
  - decreasing in level of channel fade.
- For Markov packet arrival process and Markov channel fade, optimal stationary policy is
  - increasing in buffer occupancy.
  - increasing in number of packet arrivals.
  - nothing can be said about the nature of optimal policy with respect to channel fade.

Multiuser Optimal Solution

Conclusions

- Providing QoS is one of the requirements for emerging multimedia applications over wireless networks.
- QoS in wireless network is very challenging
  - Location dependent errors
  - Time varying channel
  - Limited battery life
- In this talk, we have looked at various mechanisms that can provide
  - Fairness.
  - Delay bounded throuput guarantees.
  - Delay bouned energy efficieny.
- These are going to be important constituent of Base station scheduler for next generation wireless systems.

References(Our work) I

[1] M. Agarwal, V. S. Borkar, and A. Karandikar, “Structural properties of optimal transmission policies over a randomly varying channel,”
submitted to IEEE Transactions on Control Systems.

[2] A. Bhorkar, A. Karandikar, and V. Borkar, “Power optimal opportunistic scheduling,”
work in progress.

[3] N. Salodkar, A. Karandikar, and V. Borkar, “Efficient scheduling in fading channels,”
work in progress.

Other References I

[1] A. Parekh and R. Gallager, “A generalized processor sharing approach to flow control, the single node case,” in *IEEE INFOCOM*, May 1992.

[2] T. Nandagopal, S. Lu, and V. Bharghavan, “A unified architecture for the design and evaluation of wireless fair queueing algorithms,” in *Mobile Computing and Networking*, pp. 132–142, 1999.

[3] M. A. Arad and A. Leon-Garcia, “A generalized processor sharing approach to time scheduling in hybrid cdma/tdma.,” in *INFOCOM*, pp. 1164–1171, 1998.

[4] S. Lu, V. Bharghavan, and R. Srikant, “Fair scheduling in wireless packet networks,” *IEEE/ACM Transactions on Networking*, vol. 7, no. 4, pp. 473–489, 1999.

[5] N. Vaidya, P. Bahl, and S. Gupta, “Distributed fair scheduling in a wireless lan,” in *Sixth Annual International Conference on Mobile Computing and Networking, Boston*, August 2000.

[6] W. Pattara-atikom, S. Banergee, and P. Krishnamurthy, “Starvation prevention and quality of service in wireless lans,” in *Proceedings of the IEEE 5th Intl. Symposium on Wireless Personal Multimedia Communications (WPMC)*, Oct 2002.

Thank you.

Energy Efficient Scheduling for Multiuser system

- Design an energy efficient, opportunistic scheduler.
- The scheduler satisfies the rate guarantees
- Minimize average power

$$\text{Minimize} \quad \limsup_{M \to \infty} \frac{1}{M} \sum_{n=1}^{M} q(n),$$

- Subject to average rate constraints C_i

$$\liminf_{M \to \infty} \frac{1}{M} \sum_{n=1}^{M} \sum_{i=1}^{N} U_i(q_i(n), x_i(n))) \geq C_i \quad \forall i,$$

$$q(n) \geq 0, \sum_{i=1}^{N} y_i(n) \leq 1 \quad \forall n$$

  - U is concave differentiable function of x_i, q_i

    $U = \log(1 + x_i q_i)$

Multiuser Optimal Solution

Theorem

Optimal Policy for multiple users is to select k^{th} user and transmit with power $q_i^* = \left(\lambda_i - \frac{1}{x_i}\right)^+$.

Proof.

Sketch of Proof

- Use ergodicity of $x_i(n)$.
- Consider Lagrangian associated with (5).
- Minimize w.r.t. q first, then w.r.t. y.

$\square$

Multiuser Optimal Solution

Proof.

Cont'd..

- Optimal power for single user,

$$q_i^* = \left(\lambda_i - \frac{1}{x_i}\right)^+ \text{, where } \lambda \text{ is the Lagrange multiplier.}$$

- Minimizing w.r.t. y,

$$k = \arg\min_i \left(q_i^* - \lambda_i \left[\log(1 + q_i^* x_i) - C_i\right]\right)$$

□

Stochastic Approximation based Online Algorithm

- Estimate λ_i online

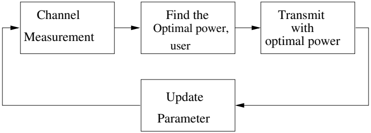

Figure: Block diagram for on-line policy

- Update Equation

$$\lambda_i(n+1) = \{\lambda_i(n) - \epsilon(n)\underbrace{[y_i(n)\log\left(1+\left(\lambda_i(n)-\frac{1}{x_i(n)}\right)^+ x_i(n)\right)] - C_i}_{h_i(\lambda)}\}^+ \quad \forall i, \qquad (5)$$

Simulations

- Rayleigh fading channel with parameter γ

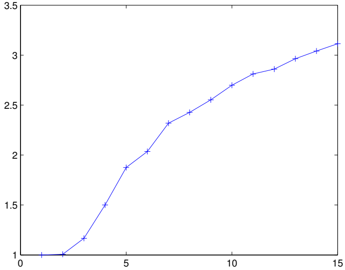

Figure: Gain of the optimal policy over variable power round robin policy, C=0.6, $\gamma = 0.7$

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