- convergence to optimal solution of (P) can be shown by using Lyapunov function approach (Wen & Arcak 04)

- Relationship to TCP-reno

  - Window evolution for congestion avoidance in TCP-reno can be approximated as

$$W(t+\delta) \approx \frac{A(t,t+\delta)}{W(t)} + \underbrace{\left(\tfrac{1}{2}\right)^{N(t,t+\delta)}}_{} W(t)$$

$$= e^{-(\ln 2) N(t,t+\delta)}$$

$$\approx 1 - (\ln 2) N(t,t+\delta)$$

where $A(t,t+\delta)$ = # ACKs in $(t,t+\delta)$

$N(t,t+\delta)$ = # losses in $(t,t+\delta)$

→ Continuous time approximation for loss probability $q(t)$, small d

$$\frac{dW}{dt} = \frac{r(t)(1-q(t))}{W(t)} - \beta\, r(t) q(t) W(t)$$

where $\beta \approx \ln 2$

$$\Rightarrow \frac{dr}{dt} = \frac{r(t)(1-q(t))}{d^2 r(t)} - \beta\, r(t)^2 q(t)$$

  - for small $q(t)$,

$$\frac{dr}{dt} \approx \frac{1}{d^2} - \beta r^2 q(t)$$

$$= \beta r^2 \left(\frac{1}{\beta d^2 r^2} - q(t)\right)$$

- from (1),

$$\frac{\partial U}{\partial r} = \frac{1}{\beta d^2 r^2}$$

$$U(r) = -\frac{1}{\beta d^2 r} \ (+\text{ const})$$

- link loss probability → price p_ℓ

path loss probability for σ →

$$q_\sigma = 1 - \prod_{\ell \in \mathcal{L}_\sigma} (1 - p_\ell)$$

$$\approx \sum_{\ell \in \mathcal{L}_\sigma} p_\ell \quad \text{for small } p_\ell,$$

q_σ

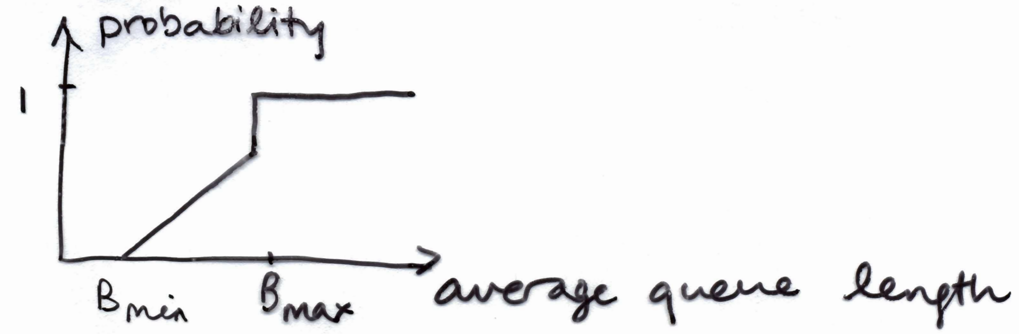
Queueing disciplines

- Queueing discipline: governs how packets are buffered & selected for transmission at a router/switch

  a) drop policy: determines which packets are dropped

    - tail drop: any packet that arrives when the buffer is full is dropped
      - simplest & most common drop policy
    - random early detection (RED): packets are dropped (or marked) with a probability that is a function of the average queue length

RED probability profile



- breaks synchronization among TCP flows, maintains small queues

b) <u>scheduling policy</u>: determines the order in which queued packets are selected for transmission

- <u>first-in-first-out (FIFO)</u> or <u>first-come-first-served (FCFS)</u>
  - packets are transmitted in the same order as they arrived
- <u>priority queueing</u>
  - packets arriving at the output link are classified into priority classes, each typically with its own FIFO queue
  - packets are transmitted from the highest priority class with a nonempty queue
  - used in the Internet to prioritize routing updates
- <u>fair queueing / round robin</u>
  - maintain a separate queue for each flow / class
  - scheduler rotates service among the flows in a fixed sequence, equally

- when a queue reaches a particular length, additional packets from the corresponding flow are discarded
- segregates traffic so that an ill-behaved flow not following the congestion control algorithm cannot arbitrarily increase its bandwidth at the expense of other flows

- <u>Weighted fair queueing</u> (WFQ)
  - similar to fair queueing in that classes/flows are served in a circular sequence, but they receive different amounts of service according to their weight
  - useful for QoS

- detailed description of FQ & WFQ in terms of fluid version called <u>Generalized Processor Sharing</u> (GPS)
- FQ, WFQ & GPS are <u>work-conserving</u>, i.e. link is not left idle as long as there is at least 1 nonempty queue