Flow Control

An Engineering Approach to Computer Networking

Flow control problem

- Consider file transfer
- Sender sends a stream of packets representing fragments of a file
- Sender should try to match rate at which receiver and network can process data
- Can't send too slow or too fast
- Too slow
    - wastes time
- Too fast
    - can lead to buffer overflow
- How to find the correct rate?

Other considerations

- Simplicity
- Overhead
- Scaling
- Fairness
- Stability

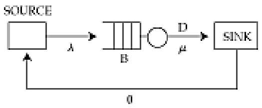
- Many interesting tradeoffs
    - overhead for stability
    - simplicity for unfairness

Where?

- Usually at transport layer
- Also, in some cases, in datalink layer

Model

- Source, sink, server, service rate, bottleneck, round trip time



Classification

- Open loop
  - Source describes its desired flow rate
  - Network *admits* call
  - Source sends at this rate
- Closed loop
  - Source monitors available service rate
    - Explicit or implicit
  - Sends at this rate
  - Due to speed of light delay, errors are bound to occur
- Hybrid
  - Source asks for some minimum rate
  - But can send more, if available

Open loop flow control

- Two phases to flow
  - Call setup
  - Data transmission
- Call setup
  - Network prescribes parameters
  - User chooses parameter values
  - Network admits or denies call
- Data transmission
  - User sends within parameter range
  - Network *polices* users
  - Scheduling policies give user QoS

Hard problems

- Choosing a descriptor at a source
- Choosing a scheduling discipline at intermediate network elements
- Admitting calls so that their performance objectives are met (*call admission control*).

Traffic descriptors

- Usually an *envelope*
    - Constrains worst case behavior
- Three uses
    - Basis for traffic contract
    - Input to *regulator*
    - Input to *policer*

Descriptor requirements

- Representativity
    - adequately describes flow, so that network does not reserve too little or too much resource
- Verifiability
    - verify that descriptor holds
- Preservability
    - Doesn’t change inside the network
- Usability
    - Easy to describe and use for admission control

Examples

- Representative, verifiable, but not useble
    - Time series of interarrival times
- Verifiable, preservable, and useable, but not representative
    - peak rate

Some common descriptors

- Peak rate
- Average rate
- Linear bounded arrival process

Peak rate

- Highest ‘rate’ at which a source can send data
- Two ways to compute it
- For networks with fixed-size packets
    - min inter-packet spacing
- For networks with variable-size packets
    - highest rate over *all* intervals of a particular duration
- Regulator for fixed-size packets
    - timer set on packet transmission
    - if timer expires, send packet, if any
- Problem
    - sensitive to extremes

Average rate

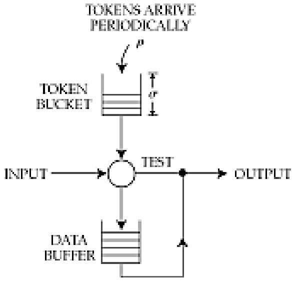
- Rate over some time period (*window*)
- Less susceptible to outliers
- Parameters: t and a
- Two types: jumping window and moving window
- Jumping window
    - over consecutive intervals of length t, only a bits sent
    - regulator reinitializes every interval
- Moving window
    - over all intervals of length t, only a bits sent
    - regulator forgets packet sent more than t seconds ago

Linear Bounded Arrival Process

- Source bounds # bits sent in any time interval by a linear function of time
- the number of bits transmitted in any active interval of length t is less than $rt + s$
- r is the long term rate
- s is the burst limit
- insensitive to outliers

Leaky bucket

- A regulator for an LBAP
- Token bucket fills up at rate r
- Largest # tokens < s



Variants

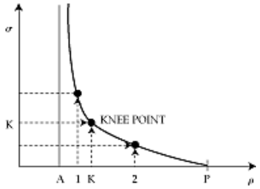
- Token and data buckets
  - Sum is what matters
- Peak rate regulator

Choosing LBAP parameters

- Tradeoff between *r* and *s*
- Minimal descriptor
  - doesn’t simultaneously have smaller *r* and *s*
  - presumably costs less
- How to choose minimal descriptor?
- Three way tradeoff
  - choice of *s* (data bucket size)
  - loss rate
  - choice of *r*

Choosing minimal parameters

- Keeping loss rate the same
  - if *s* is more, *r* is less (smoothing)
  - for each *r* we have least *s*
- Choose knee of curve



LBAP

- Popular in practice and in academia
  - sort of representative
  - verifiable
  - sort of preservable
  - sort of usable
- Problems with multiple time scale traffic
  - large burst messes up things

Open loop vs. closed loop

- Open loop
  - describe traffic
  - network admits/reserves resources
  - regulation/policing
- Closed loop
  - can't describe traffic or network doesn't support reservation
  - monitor available bandwidth
    - perhaps allocated using GPS-emulation
  - adapt to it
  - if not done properly either
    - too much loss
    - unnecessary delay

Taxonomy

- First generation
  - ignores network state
  - only match receiver
- Second generation
  - responsive to state
  - three choices
    - State measurement
      - explicit or implicit
    - Control
      - flow control window size or rate
    - Point of control
      - endpoint or within network

Explicit vs. Implicit

- Explicit
  - Network tells source its current rate
  - Better control
  - More overhead
- Implicit
  - Endpoint figures out rate by looking at network
  - Less overhead
- Ideally, want overhead of implicit with effectiveness of explicit

Flow control window

- Recall error control window
- Largest number of packet outstanding (sent but not acked)
- If endpoint has sent all packets in window, it must wait => slows down its rate
- Thus, window provides *both* error control and flow control
- This is called *transmission* window
- Coupling can be a problem
  - Few buffers are receiver => slow rate!

Window vs. rate

- In adaptive rate, we directly control rate
- Needs a timer per connection
- Plusses for window
  - no need for fine-grained timer
  - self-limiting
- Plusses for rate
  - better control (finer grain)
  - no coupling of flow control and error control
- Rate control must be careful to avoid overhead and sending too much

Hop-by-hop vs. end-to-end

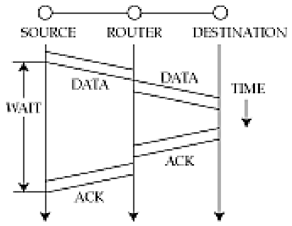
- Hop-by-hop
  - first generation flow control at each link
    - next server = sink
  - easy to implement
- End-to-end
  - sender matches all the servers on its path
- Plusses for hop-by-hop
  - simpler
  - distributes overflow
  - better control
- Plusses for end-to-end
  - cheaper

On-off

- Receiver gives ON and OFF signals
- If ON, send at full speed
- If OFF, stop
- OK when RTT is small
- What if OFF is lost?
- Bursty
- Used in serial lines or LANs

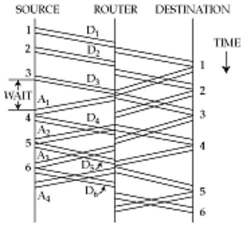
Stop and Wait

- Send a packet
- Wait for ack before sending next packet



Static window

- Stop and wait can send at most one pkt per RTT
- Here, we allow multiple packets per RTT (= transmission window)



What should window size be?

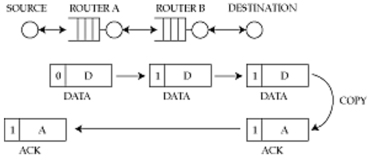
- Let bottleneck service rate along path = b pkts/sec
- Let round trip time = R sec
- Let flow control window = w packet
- Sending rate is w packets in R seconds = w/R
- To use bottleneck w/R > b => w > bR
- This is the *bandwidth delay product* or *optimal window size*

Static window

- Works well if b and R are fixed
- But, bottleneck rate changes with time!
- Static choice of w can lead to problems
  - too small
  - too large
- So, need to adapt window
- Always try to get to the *current* optimal value

DECbit flow control

- Intuition
  - every packet has a bit in header
  - intermediate routers set bit if queue has built up => source window is too large
  - sink copies bit to ack
  - if bits set, source reduces window size
  - in steady state, oscillate around optimal size

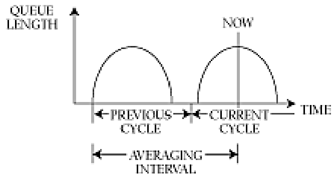


DECbit

- When do bits get set?
- How does a source interpret them?

DECbit details: router actions

- Measure *demand* and *mean queue length* of each source
- Computed over queue regeneration cycles
- Balance between sensitivity and stability



Router actions

- If mean queue length > 1.0
  - set bits on sources whose demand exceeds fair share
- If it exceeds 2.0
  - set bits on everyone
  - panic!

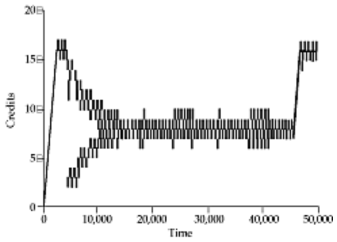
Source actions

- Keep track of bits
- Can’t take control actions too fast!
- Wait for past change to take effect
- Measure bits over past + present window size
- If more than 50% set, then decrease window, else increase
- Additive increase, multiplicative decrease

Evaluation

- Works with FIFO
  - but requires per-connection state (demand)
- Software
- But
  - assumes cooperation!
  - conservative window increase policy

Sample trace



TCP Flow Control

- Implicit
- Dynamic window
- End-to-end

- Very similar to DECbit, but
  - no support from routers
  - increase if no loss (usually detected using timeout)
  - window decrease on a timeout
  - additive increase multiplicative decrease

TCP details

- Window starts at 1
- Increases exponentially for a while, then linearly
- Exponentially => doubles every RTT
- Linearly => increases by 1 every RTT
- During exponential phase, every ack results in window increase by 1
- During linear phase, window increases by 1 when # acks = window size
- Exponential phase is called *slow start*
- Linear phase is called *congestion avoidance*

More TCP details

- On a loss, current window size is stored in a variable called *slow start threshold* or *ssthresh*
- Switch from exponential to linear (slow start to congestion avoidance) when window size reaches threshold
- Loss detected either with timeout or *fast retransmit* (duplicate cumulative acks)
- Two versions of TCP
  - Tahoe: in both cases, drop window to 1
  - Reno: on timeout, drop window to 1, and on fast retransmit drop window to half previous size (also, increase window on subsequent acks)

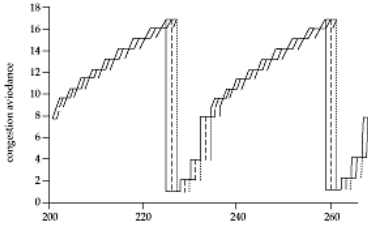
TCP vs. DECbit

- Both use dynamic window flow control and additive-increase multiplicative decrease
- TCP uses implicit measurement of congestion
  - probe a black box
- Operates at the *cliff*
- Source does not filter information

Evaluation

- Effective over a wide range of bandwidths
- A lot of operational experience
- Weaknesses
  - loss => overload? (wireless)
  - overload => self-blame, problem with FCFS
  - ovelroad detected only on a loss
    - in steady state, source *induces* loss
  - needs at least bR/3 buffers per connection

Sample trace



TCP Vegas

- Expected throughput = transmission_window_size/propagation_delay
- Numerator: known
- Denominator: measure *smallest* RTT
- Also know *actual* throughput
- Difference = how much to reduce/increase rate
- Algorithm
    - send a special packet
    - on ack, compute expected and actual throughput
    - (expected - actual)* RTT packets in bottleneck buffer
    - adjust sending rate if this is too large
- Works better than TCP Reno

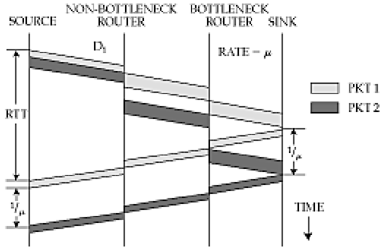
NETBLT

- First rate-based flow control scheme
- Separates error control (window) and flow control (no *coupling*)
- So, losses and retransmissions do not affect the flow rate
- Application data sent as a series of buffers, each at a particular rate
- Rate = (burst size + burst rate) so granularity of control = burst
- Initially, no adjustment of rates
- Later, if received rate < sending rate, multiplicatively decrease rate
- Change rate only once per buffer => slow

Packet pair

- Improves basic ideas in NETBLT
    - better measurement of bottleneck
    - control based on prediction
    - finer granularity
- Assume all bottlenecks serve packets in round robin order
- Then, spacing between packets at receiver (= ack spacing) = 1/(rate of slowest server)
- If *all* data sent as paired packets, no distinction between data and probes
- Implicitly determine service rates if servers are round-robin-like

Packet pair



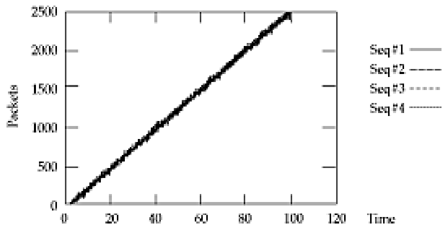
Packet-pair details

- Acks give time series of service rates in the past
- We can use this to predict the next rate
- Exponential averager, with fuzzy rules to change the averaging factor
- Predicted rate feeds into flow control equation

Packet-pair flow control

- Let X = # packets in bottleneck buffer
- S = # outstanding packets
- R = RTT
- b = bottleneck rate
- Then, X = S - Rb (assuming no losses)
- Let l = source rate
- l(k+1) = b(k+1) + (setpoint -X)/R

Sample trace



ATM Forum EERC

- Similar to DECbit, but send a whole cell’s worth of info instead of one bit
- Sources periodically send a Resource Management (RM) cell with a *rate request*
    - typically once every 32 cells
- Each server fills in RM cell with current share, if less
- Source sends at this rate

ATM Forum EERC details

- Source sends Explicit Rate (ER) in RM cell
- Switches compute source share in an unspecified manner (allows competition)
- Current rate = allowed cell rate = ACR
- If ER > ACR then ACR = ACR + RIF * PCR else ACR = ER
- If switch does not change ER, then use DECbit idea
  - If CI bit set, ACR = ACR (1 - RDF)
- If ER < AR, AR = ER
- Allows interoperability of a sort
- If idle 500 ms, reset rate to Initial cell rate
- If no RM cells return for a while, ACR *= (1-RDF)

Comparison with DECbit

- Sources know exact rate
- Non-zero Initial cell-rate => conservative increase can be avoided
- Interoperation between ER/CI switches

Problems

- RM cells in data path a mess
- Updating sending rate based on RM cell can be hard
- Interoperability comes at the cost of reduced efficiency (as bad as DECbit)
- Computing ER is hard

Comparison among closed-loop schemes

- On-off, stop-and-wait, static window, DECbit, TCP, NETBLT, Packet-pair, ATM Forum EERC
- Which is best? No simple answer
- Some rules of thumb
  - flow control easier with RR scheduling
    - otherwise, assume cooperation, or police rates
  - explicit schemes are more robust
  - hop-by-hop schemes are more resposive, but more comples
  - try to separate error control and flow control
  - rate based schemes are inherently unstable unless well-engineered

Hybrid flow control

- Source gets a minimum rate, but can use more
- All problems of both open loop and closed loop flow control
- Resource partitioning problem
  - what fraction can be reserved?
  - how?