Measurement-Based Dynamic Traffic Engineering Using Overlay Architecture

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LTS Review

June 27th, 2003

Introduction

- Routing in the Internet
  - Problems with Shortest Path Routing
    - Inefficient use of network resources
    - Limited control capabilities
    - Modifying link metrics tends to have network wide effects. i.e., possibility of undesirable and unanticipated traffic shifts.
    - Lacking the capability of load balancing between *different cost* paths.
    - Unable to consider traffic/policy constraints. e.g. avoiding certain links for certain source-destination pairs.
  - Multi-path Solutions

Existing Algorithms

- Multi-path Solutions
  - Existing optimal multi-path algorithms
    - J. N.Tsitsiklis, D.P. Bertsekas
      IEEE Trans. Automat. Control, 1986
    - A. Elwalid, C. Jin, S.Low, I. Widjaja (MATE)
      IEEE INFOCOM, 2001
  - Both algorithms assume the availability of *analytical* cost gradient function.

$$x(k+1) = [x(k) - a_k \nabla C(x(k))]^+$$

    - $\nabla C(x(k))$ is the cost gradient vector.
    - Not practical due to the dynamic nature of traffic patterns in IP Networks (i.e., assumption of independent M/M/1 queues – Jacksonian Networks).
    - Only noisy measurements available

Approach - Stochastic Approximation (SA)

- MATE refers to this problem
  - An implementation that uses estimates of the cost gradient instead of analytical functions.
  - However, the theoretical analysis does not cover the estimation process at all.
  - Under these conditions, the convergence of the algorithm is not guaranteed unless specific conditions are met.
- Possible solution under these assumptions:
  - Stochastic Approximation (SA):
    - A recursive procedure for finding roots of equations in the presence of noisy measurements.
    - Useful tool for finding extrema of functions.

$$x(k+1) = [x(k) - a_k \hat{g}(x(k))]^+$$

SA Overview

- Alternative SA methods based on different gradient estimation approaches:
  - Finite Differences Stochastic Approximation (FDSA)
  - Simultaneous Perturbation Stochastic Approximation (SPSA)
- FDSA:
  - Motivated from the definition of gradient
  - Each component of $x(k)$ is perturbed one at a time and corresponding measurements are obtained.
  - i^{th} *component of* $\hat{g}(x(k))$ *is given by:*

$$\hat{g}_i(x(k)) = \frac{y(x(k)+c_k e_i) - y(x(k)-c_k e_i)}{2c_k}$$

  - Remark: Implementation presented in MATE relies on the FDSA idea.

SA Overview – Simultaneous Perturbation SA

- SPSA:
  - All elements of $x(k)$ are *randomly* perturbed *together* to obtain two measurements y(.).
  - Each component of $\hat{g}(x(k))$ formed from a ratio :

$$\hat{g}_i(x(k)) = \frac{y(x(k)+c_k\Delta_k) - y(x(k)-c_k\Delta_k)}{2c_k\Delta_{ki}}$$

  where Δ_k is the random perturbation vector with a specific random distribution satisfying necessary conditions.
  - The measurements can be noisy as long as the difference of the noise terms have zero mean.

SPSA vs. FDSA

- Benefits of SPSA over FDSA:
  - SPSA algorithm requires only two measurements independent of number of parameters being optimized, while FDSA uses 2p measurements to approximate the gradient, p being the dimension of the gradient vector.
  - It has been shown that under reasonably general conditions, SPSA and FDSA achieve same level of statistical accuracy for a given number of iterations even though SPSA uses p times fewer function evaluations than FDSA.
  - Result confirmed in many numerical studies, even in cases where p is on the order of several hundreds or thousands.

SPSA-Based Multi-Path Routing

- Promising results from the routing problem point of view
  - Considering that each measurement is costly and time-consuming in a networking environment, use of SPSA in the multi-path routing problem suggests fast response to changing networking conditions than the existing methods.
  - With some technical modifications, SPSA algorithm perfectly fits to the optimal routing problem.
- The Proposed Optimal Multi-path Routing Algorithm:
  - Each source-destination (SD) pair runs the SPSA algorithm independently and asynchronously to minimize the cost along its paths.
  - Only the local state information obtained from the paths between the SD pair is needed.
  - The overall system converges to the global optimum.

Measurement

- Measurement Process
  - The measurements of each SD pair overlaps in time, creating noise for each other.
  - Due to statistical characteristics of the random perturbations, the noise term created by this simultaneous operation has a zero mean and therefore does not prevent convergence.
  - As the asynchronism between SD pairs increases, the magnitude of this noise term decreases.
  - From Law of Large Numbers, it will go to zero as the number of SD pairs increases as well.
  - The gains from the reduced measurement time clearly dominates the side-effects of simultaneous operation of SD pairs.

Benefits of SPSA-Based Optimal Routing

- Merits of the optimal routing algorithm
  - Distributed
  - Asynchronous
  - Depends on local state information
  - Only noisy measurement required
  - Considerably reduces the measurement time required for estimation process and achieves faster convergence. (i.e. faster response to changes in the network conditions.)

Applications

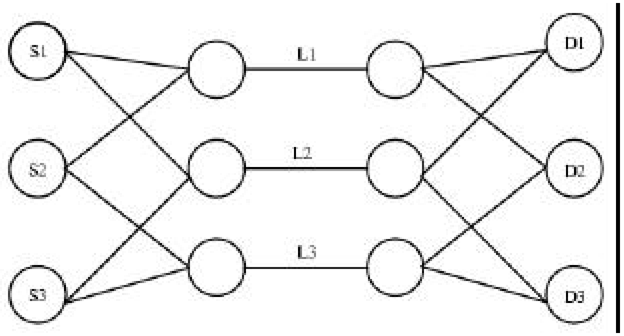
- Implementation

  - Overlay routing
    - Establishment of alternative paths between SD pairs by relaying packets along the overlay paths
    - Efficient distribution of local state information to the source nodes.

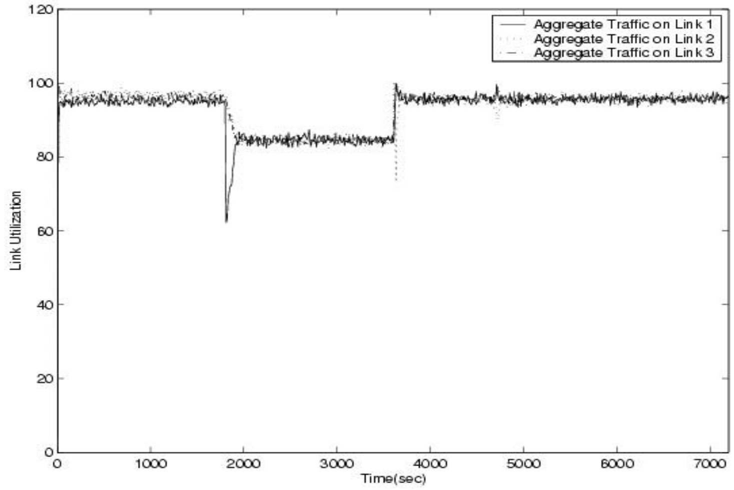
  - MPLS based networks
    - Can be implemented in MPLS based networks as well.

Simulation Results – (1)

- Experiments
  - Comparison with MATE



Network Topology

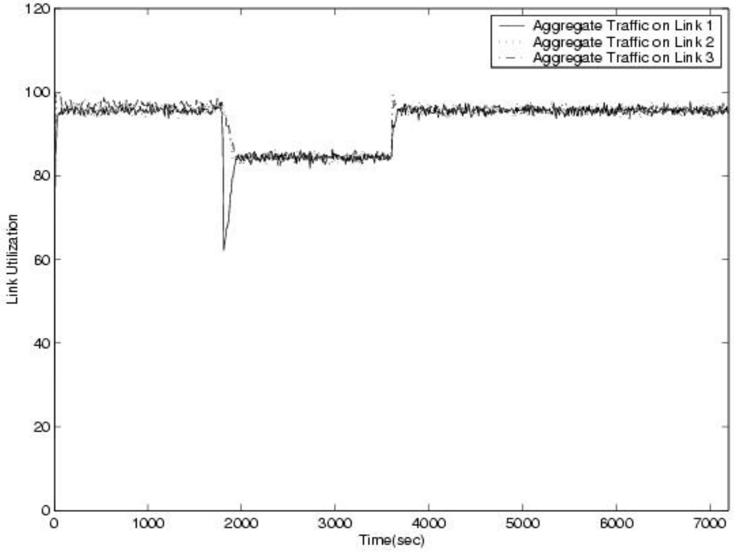


Offset = 50 msec

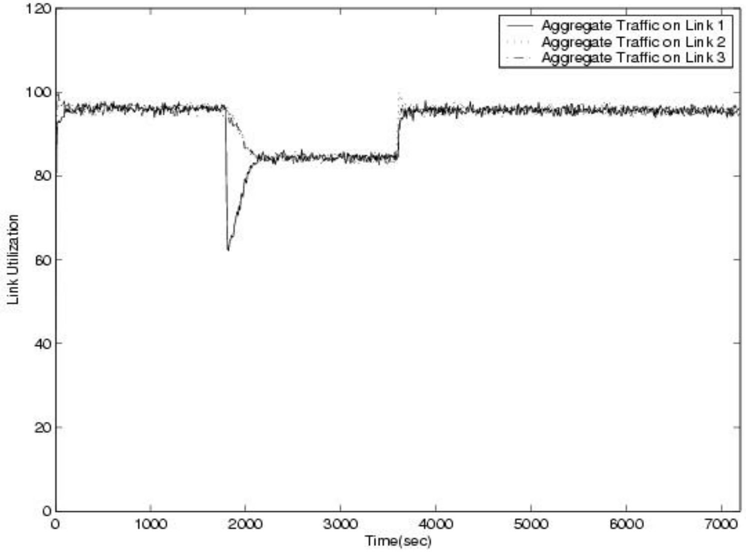
  - Three SD pairs, each having two alternative paths.
  - SD pairs start running the optimal algorithm independently at a random offset time.
  - All links are 45 Mbps.

Simulation Results – (1) cont'd

- Experiments
  - Effect of Increasing Asynchronism



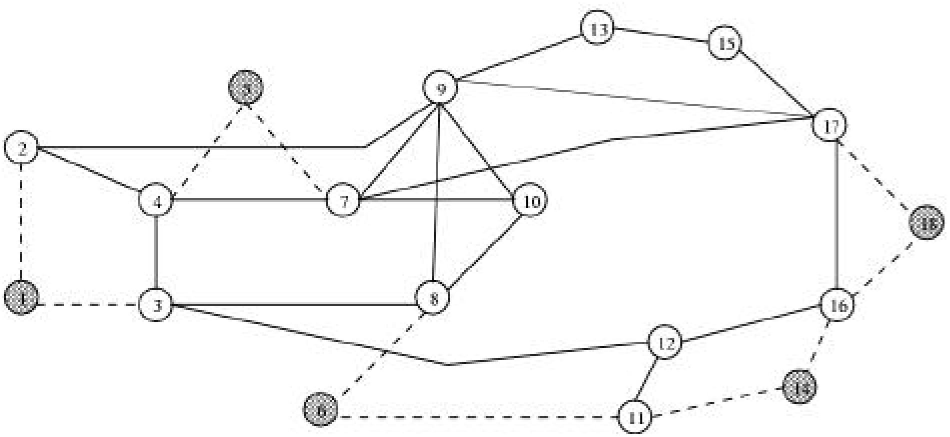
Offset = 0.2 sec



Offset = 0.5 sec

Simulation Results – (2)

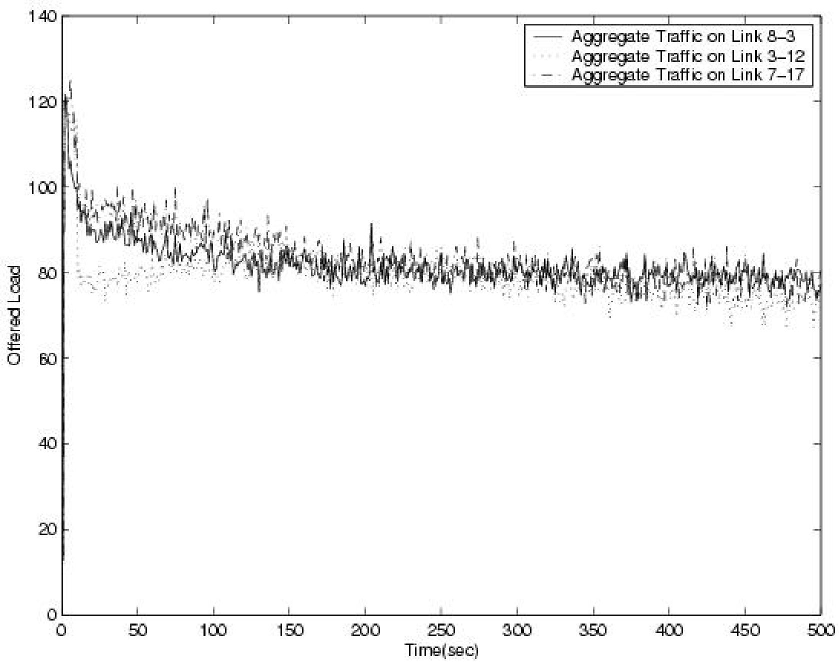
- Experiments
  - ISP topology analysis

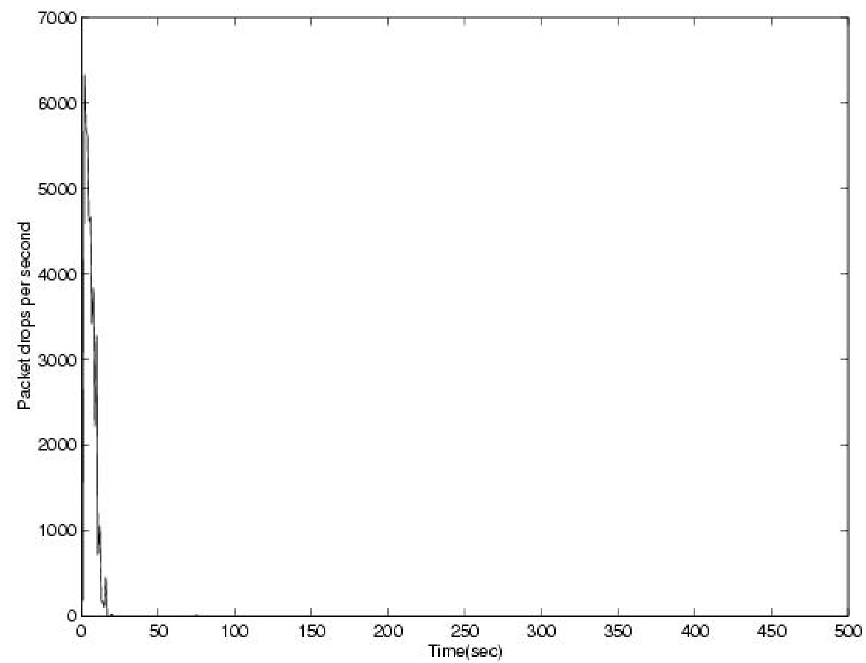


  - Nodes 1,5,6,14 and 18 are SD nodes (i.e. 20 SD pairs).
  - Dashed links are 50 Mbps, Solid links are 20 Mbps.
  - Each SD pair has at least three alternative paths established using overlaying idea.
  - Each SD pair creates 12 Mbps Poisson traffic.

Simulation Results – (2) cont'd

- Experiments
  - Effect of Multiple SD pairs working simultaneously





Simulation Results – (2) cont'd

- Experiments
  - Effect of uncontrolled cross traffic
  - Same setup except SD pair Poisson rate is 10.5 Mbps.
  - At 400 sec, cross traffic enters at link 3-12