Network Loss Inference with Second Order Statistics of End-to-End Flows

Hung X. Nguyen and Patrick Thiran

School of CCS, EPFL

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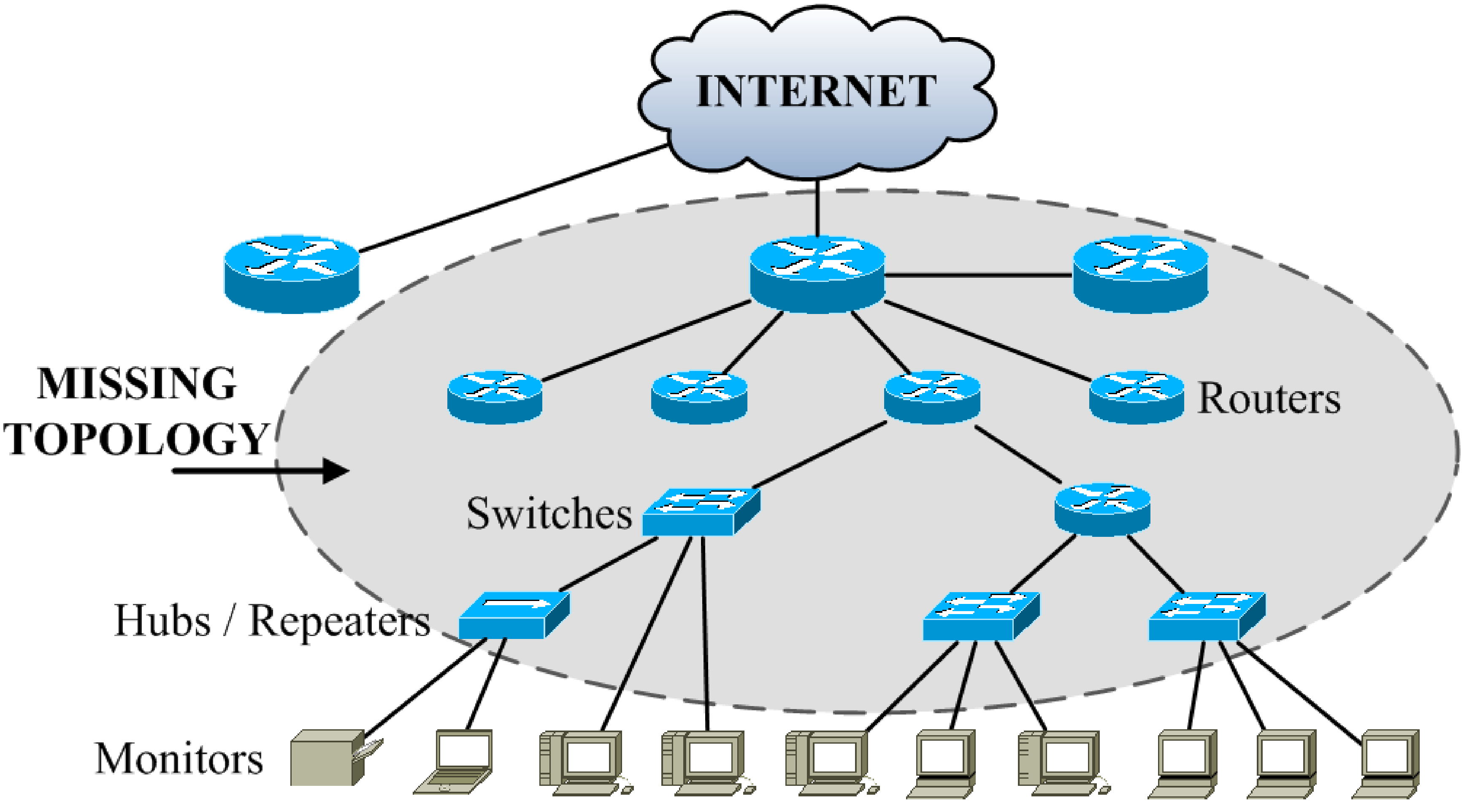
My INFOCOM 2011 submission



My INFOCOM 2011 submission

- Problem solved
  - Cast the Tree Topology Inference problem → BICA
  - Derive seqBICA and incBICA
  - Better rate of convergence (compare to BLTP)
- Current problems
  - High computation complexity
  - Multicast is limited
  - Missing real-life experiments

Unicast probes
PlanetLab exp

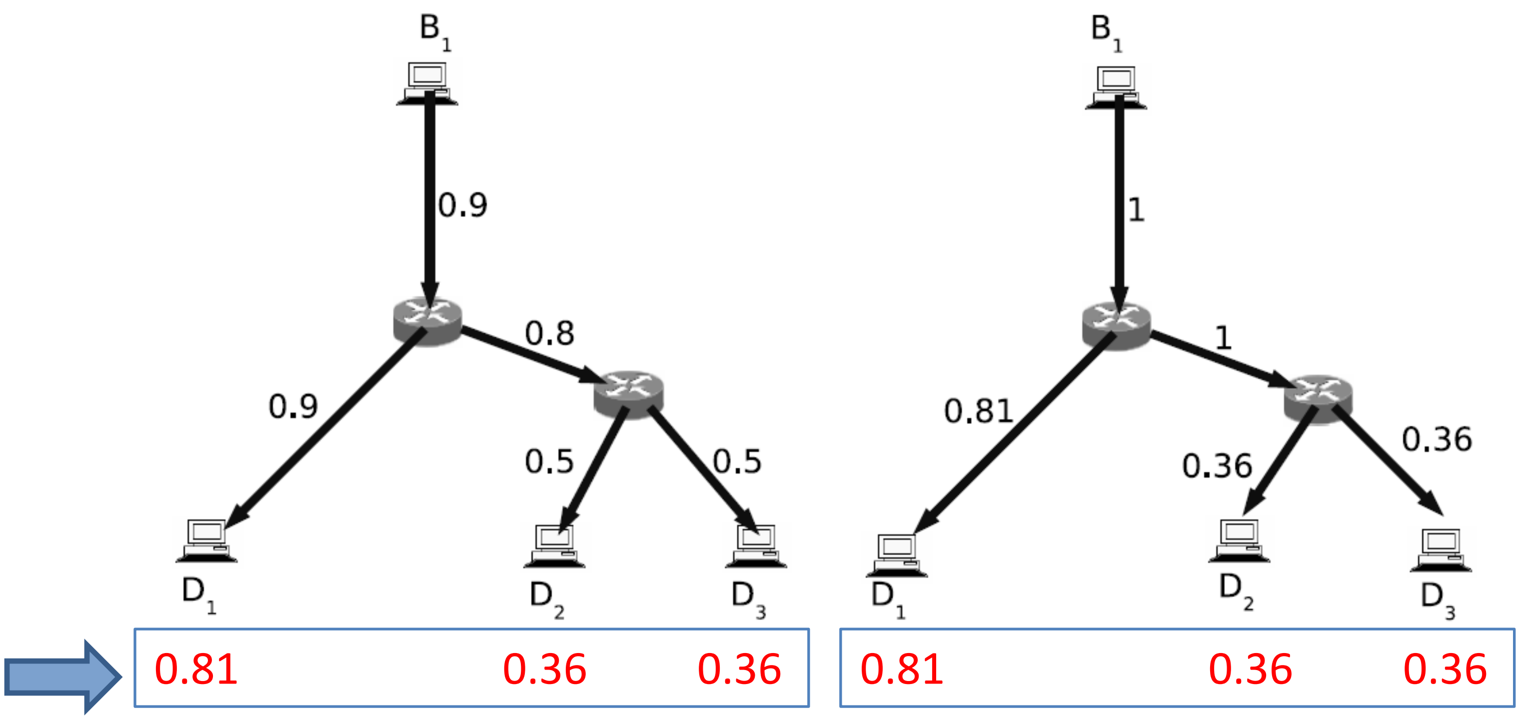
Outline

1. Problem definition
2. Network model and assumptions
3. The algorithm
4. Simulation and Experiments
5. Conclusion

1. Problem definition

- Given the Network Topology, compute the link loss rates from end-to-end measurements
- Under-determined problem

End-to-end observation

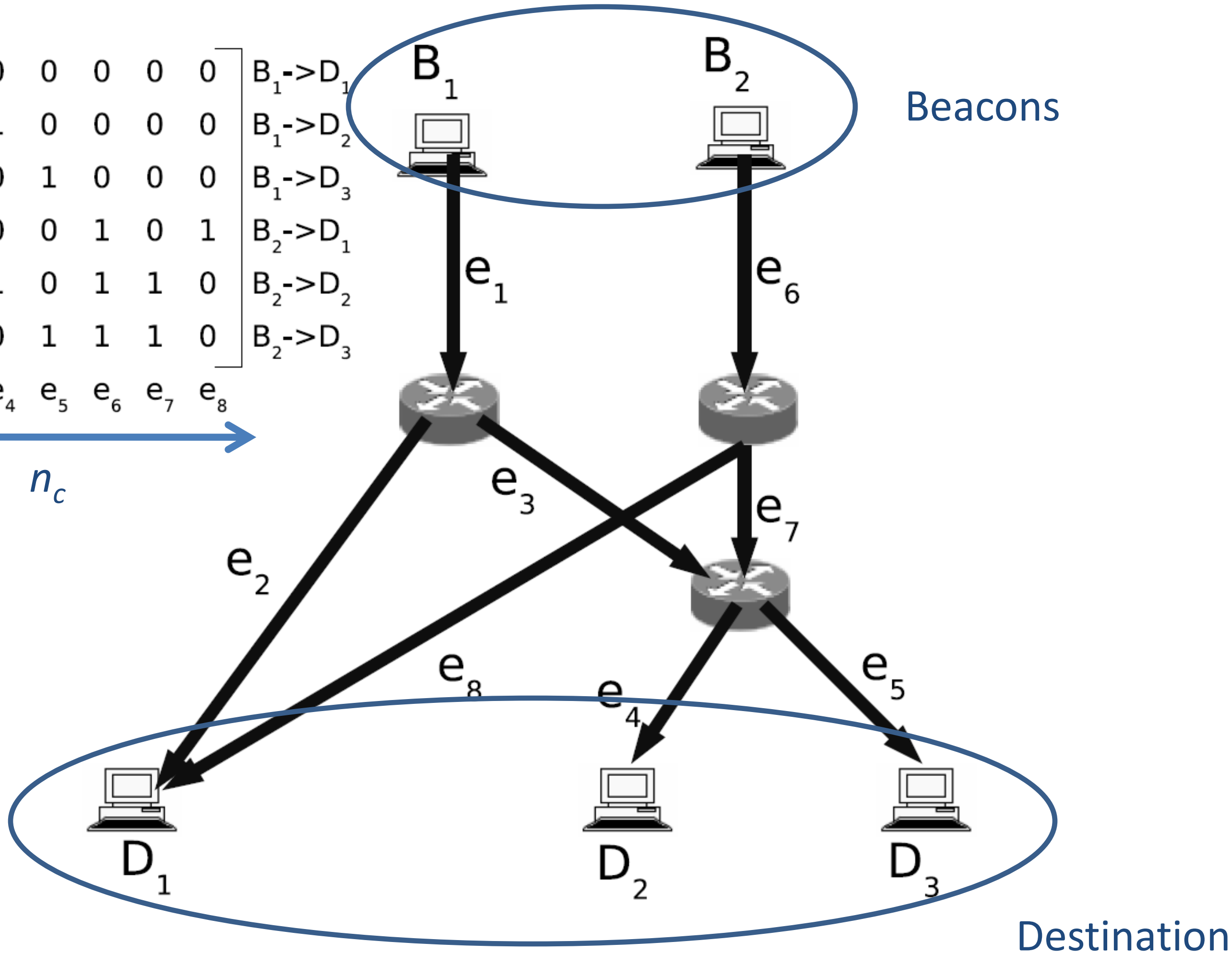


2. Network model

$$
\begin{array}{c}
R = \left[\begin{array}{cccccccc}
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 1 & 0
\end{array}\right]
\begin{array}{l}
B_1\text{->}D_1 \\
B_1\text{->}D_2 \\
B_1\text{->}D_3 \\
B_2\text{->}D_1 \\
B_2\text{->}D_2 \\
B_2\text{->}D_3
\end{array}
\\
\begin{array}{cccccccc}
e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & e_7 & e_8
\end{array}
\end{array}
$$

n_p

n_c

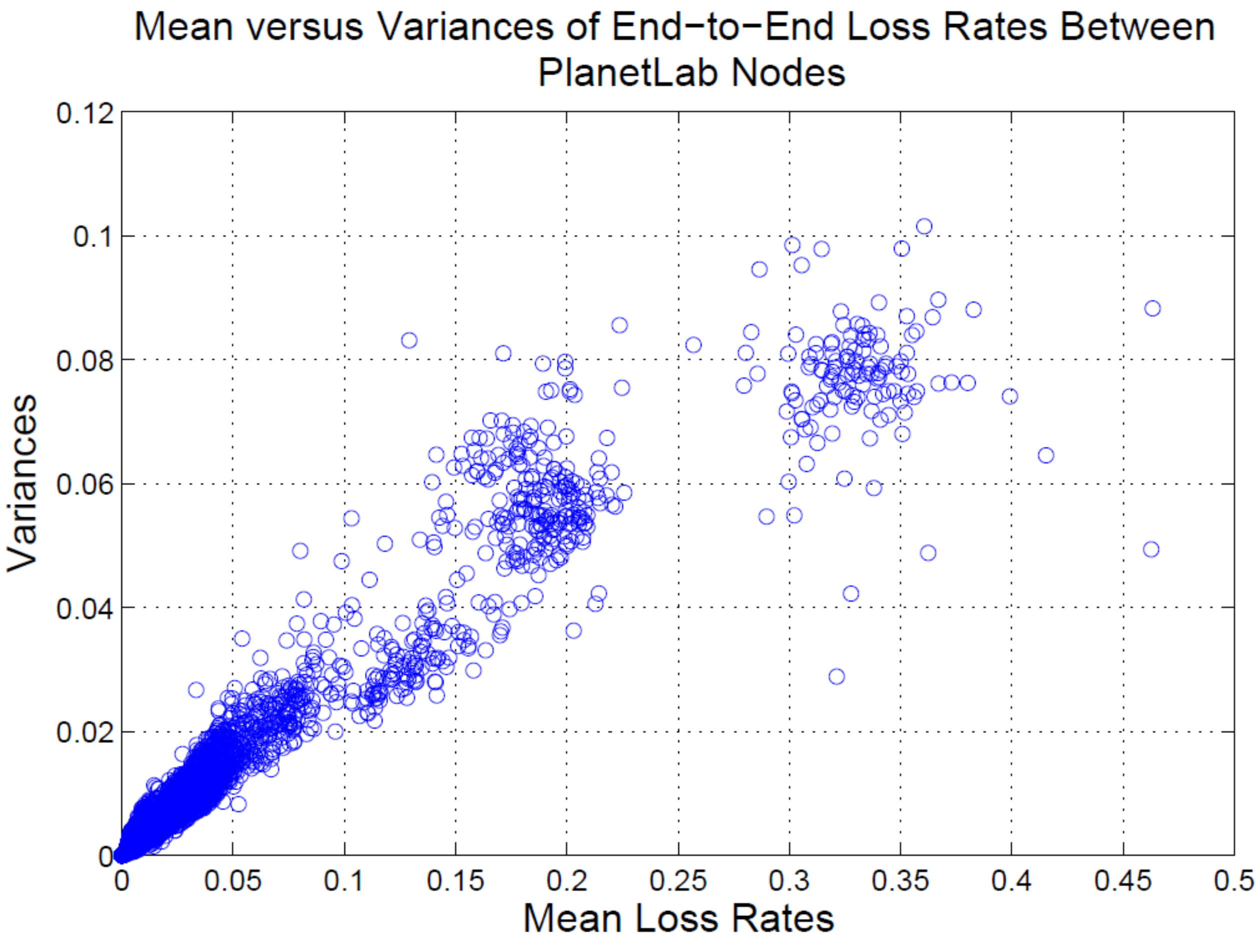


2. Assumptions

- $\widehat{\phi}_{e_k}$: transmission rate on link e_k
- $\widehat{\phi}_{i,e_k}$: transmission rate of path *i* on link e_k
- $\widehat{\phi}_i$: transmission rate of path *i*
- $Y_i = \log \widehat{\phi}_i$ and $X_k = \log \widehat{\phi}_{e_k}$

Network topology	End-to-end probes
• **T.1 Time-invariant routing:** R remains unchanged throughout the measurement period. • **T.2 No route fluttering:** There is no pair of paths P_i and $P_{i'}$ that share two links e_j and $e_{j'}$ without also sharing all the links located in between e_j and $e_{j'}$. That is, the two paths never meet at one link, diverge, and meet again further away at another link.	• **S.1 Identical sampled rates:** $\widehat{\phi}_{i,e_k} = \widehat{\phi}_{e_k}$ almost surely (a.s.) for all paths P_i that traverse e_k. • **S.2 Link independence:** The random variables X_k are independent. • **S.3 Monotonicity of variance:** The variance v_k of X_k is a non-decreasing function of $1 - \phi_{e_k}$.

2. Assumptions



2. Problem formulation

- Let

$$\mathbf{Y} = [Y_1 \ Y_2 \ldots \ Y_{n_p}]^T \text{ and } \mathbf{X} = [X_1 \ X_2 \ldots \ X_{n_c}]^T$$

- Now we need to solve

$$\mathbf{Y} = R\mathbf{X}.$$

- Unfortunately, *R* is (always) rank deficient

3. The algorithm

- Define the covariance matrices of **X** and **Y**

$$\Gamma_{\mathbf{X}} = \mathrm{diag}(\mathbf{v}) = \mathrm{diag}([v_1\ v_2\ \ldots v_{n_c}])$$

$$\Sigma = \begin{bmatrix} \sigma^2_{Y_1} & \mathrm{COV}[Y_1, Y_2] & \ldots & \mathrm{COV}[Y_1, Y_{n_p}] \\ \mathrm{COV}[Y_2, Y_1] & \sigma^2_{Y_2} & \ldots & \mathrm{COV}[Y_2, Y_{n_p}] \\ \vdots & \ldots & \ddots & \vdots \\ \mathrm{COV}[Y_{n_p}, Y_1] & \mathrm{COV}[Y_{n_p}, Y_2] & \ldots & \sigma^2_{Y_{n_p}} \end{bmatrix}$$

- From $\mathbf{Y} = R\mathbf{X}$. we have $\boxed{\Sigma = R\Gamma_{\mathbf{X}} R^T = R\mathrm{diag}(\mathbf{v})R^T}$

- Define augmented matrix A

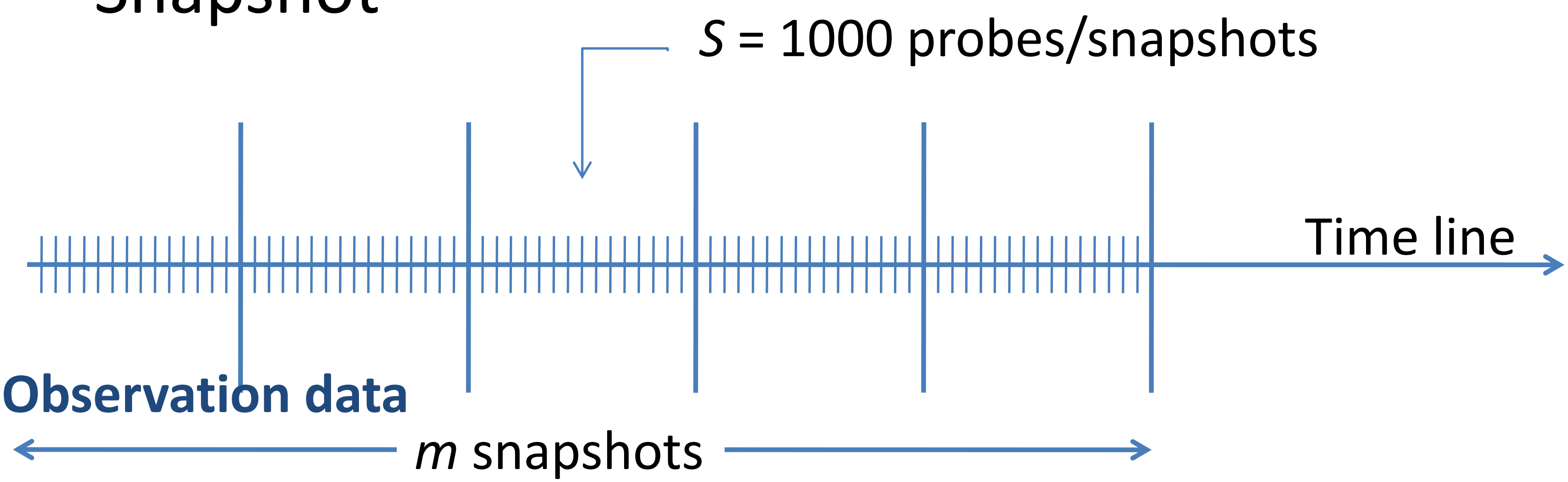
DEFINITION 1. *Let A be the augmented matrix of dimension $n_p(n_p+1)/2 \times n_c$ whose rows consist of the rows of R and the component wise products of each pair of different rows from R. The rows of A are arranged as follows: $\mathbf{A}_{((i-1)\times n_p+(j-i)+1)*} = \mathbf{R}_{i*} \otimes \mathbf{R}_{j*}$ for all $1 \le i \le j \le n_p$.*

$$R = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \end{bmatrix}, \quad A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \end{bmatrix}$$

3. The algorithm

- LEMMA 1. *The equations* $\Sigma = R\,diag(\mathbf{v})R^T$ *are equivalent to the equations* $\boldsymbol{\Sigma}^* = A\mathbf{v}$, *where* $\boldsymbol{\Sigma}^*$ *is a vector of length* $n_p(n_p+1)/2$ *and* $\Sigma^*_{(i-1)n_p+j-i+1} = \Sigma_{i,j}$ *for all* $1 \le i \le j \le n_p$.

- Snapshot



3. The algorithm

- From *m* previous snapshots, calculate

$$\widehat{\Sigma}_{ii'} = \frac{1}{m-1}\sum_{l=1}^{m} Y_i^{(l)} Y_{i'}^{(l)} - \overline{Y}_i^{(l)} \overline{Y}_{i'}^{(l)}, 1 \le i \le i' \le n_p$$

- Then we can calculate $\widehat{\Sigma}^*$ and solve

$$\widehat{\Sigma}^* = A\mathbf{v}$$

- Eliminate good links:
  - Sort links by their variances $v_1 \le v_2 \le \ldots \le v_{n_c}$
  - Remove columns in *R* and entries in **X** until *R* is full rank, we now have R^* and $\mathbf{X}^*$

- Finally solve $\mathbf{Y} = R^* \mathbf{X}^*$

3. The algorithm

Input: The reduced routing matrix R and $m+1$
snapshots: $\mathcal{Y} = \{\mathbf{y}^1, \mathbf{y}^2, ..., \mathbf{y}^m, \mathbf{y}^{m+1}\}$.

Phase 1 (Learning the link variances):
Solve (8) with the first m snapshots $\{\mathbf{y}^1, \mathbf{y}^2, ..., \mathbf{y}^m\}$
to find v_k for all links $e_k \in \mathcal{E}_c$.

Phase 2 (Inferring link loss rates):
Step 1. Sort v_k in increasing order.
Step 2. Initialize $R^* = R$.
(Loop) While R^* is not of full column rank
remove R^*_{1*} from R^*.
Step 3. Solve (9) for snapshot $(m+1)$th.
Approximate $\phi_{e_k} \approx 1$ for all links e_k
whose columns were removed from R.

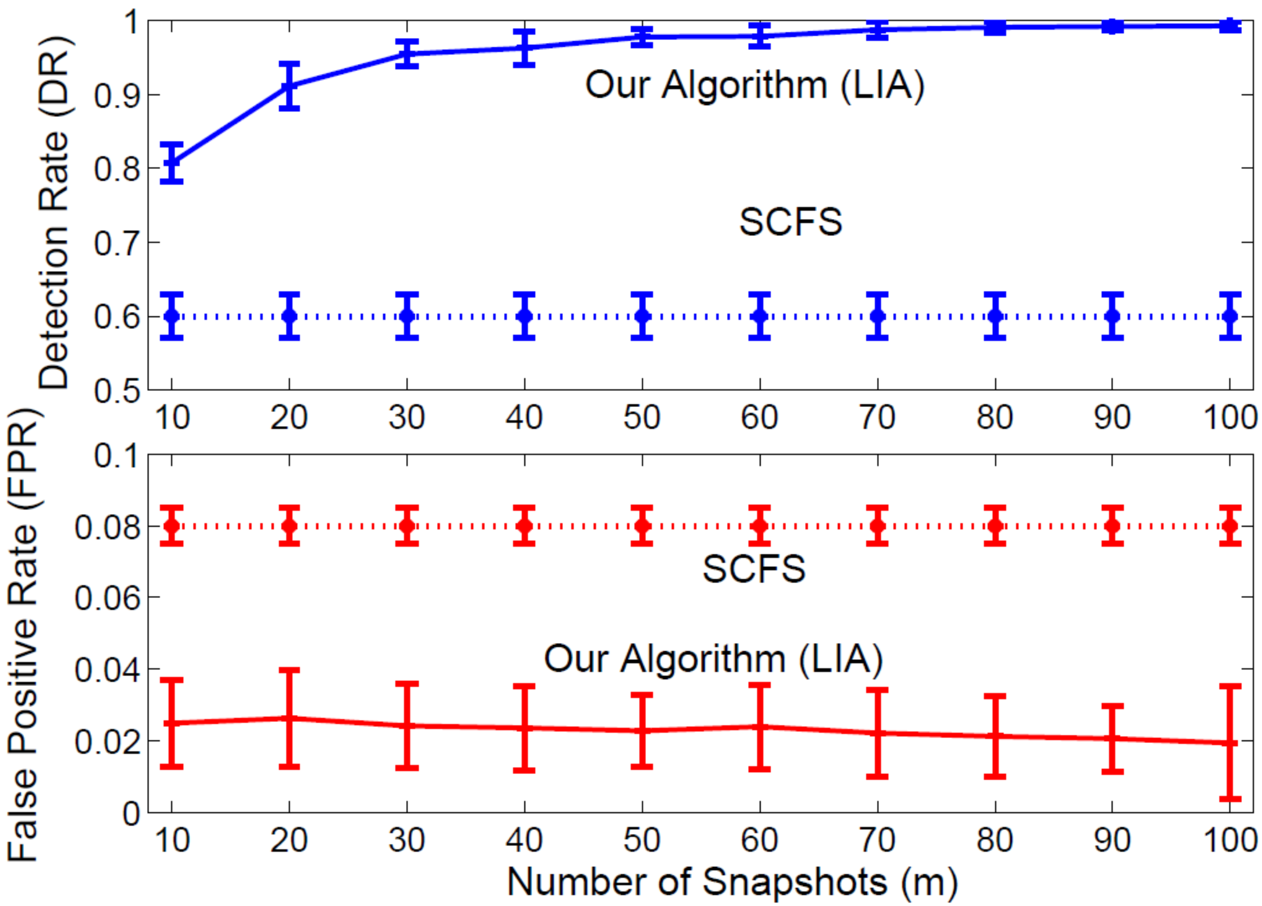
Output: Link transmission rates $\phi = [\phi_1 \, \phi_2 \, \ldots \, \phi_{n_c}]^T$
of the $(m+1)$th snapshot.

Loss Inference Algorithm (LIA)

4. Simulation

- Matlab implementation
- Congested links = 10%
- Loss rate
  - Good links: [0, 0.002]
  - Congested links: [0.002, 0.2]
- Bernoulli/Gilbert packet loss model
- S = 1000 probes for each snapshot
- Performance metrics
  - Detection rate
  - False positive rate

4. Simulation

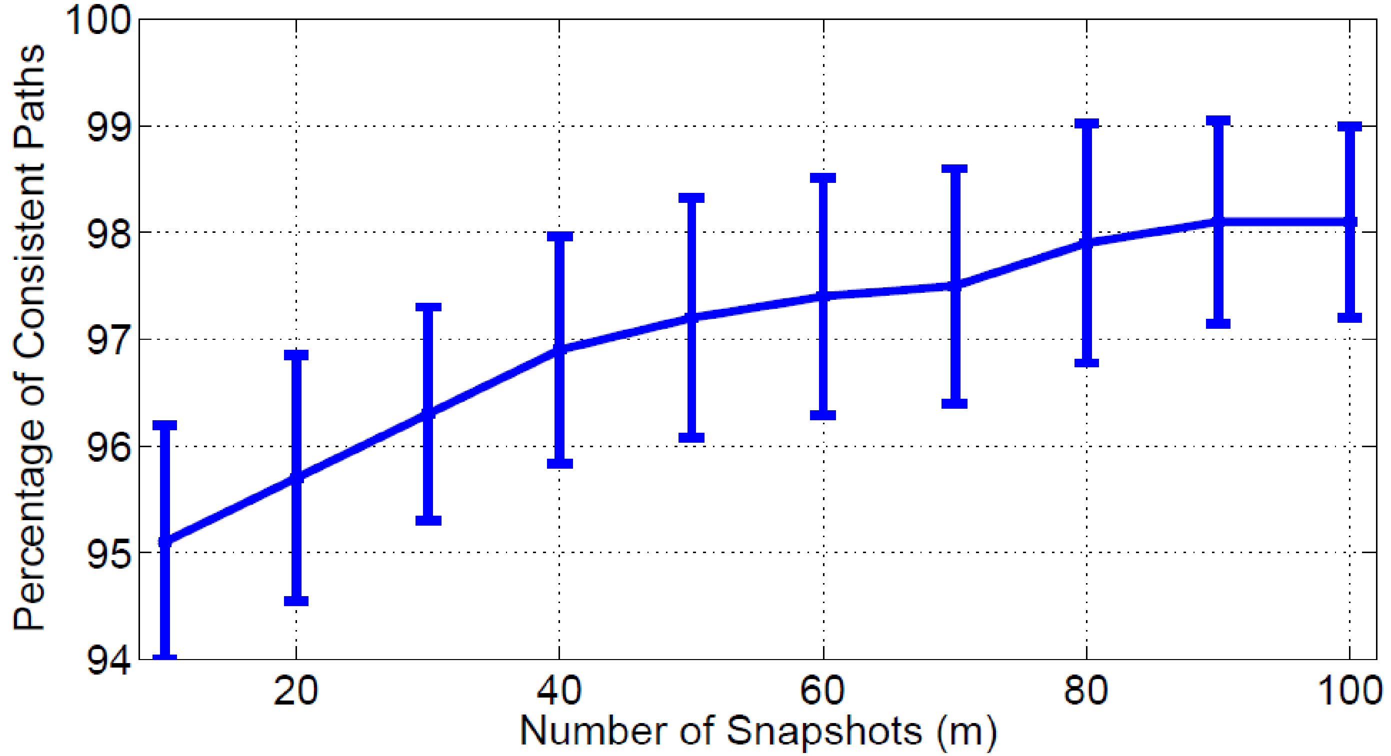


4. Internet experiment

- PlanetLab network with 716 hosts (only 381 hosts cooperate) on April 20, 2007
- Use Traceroute to measure network topology (potential noise in R)
- Remove fluttering paths from R
- Probe = UDP packet (40 bytes)
- Avoid creating probe congestion: probing rate = 100KB/sec
- Cross validation method

4. Internet experiment

- A path is consistent if: $$\left| \widehat{\phi}_i - \prod_{e_k \in P_i \cap \mathcal{E}_{\inf}} \phi_{e_k} \right| \leq \epsilon, \quad \epsilon = 0.005.$$



5. Conclusion

- Link Lost Rate Inference by using second-order statistics
- What can be applied to our research?
  - Link delay inference
  - PlanetLab experiments methodology
  - Covariance exploitation