A Proposal of an Efficient Traffic Matrix Estimation under Packet Drops

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***Abstract*—Traffic matrix (TM) estimation has been extensively studied for decades. Although conventional estimation techniques assume that traffic volumes are unchanged between origins and destinations, packets are often discarded on a path due to traffic burstiness, silent failures, etc. This paper proposes a novel TM estimation method that works correctly even under packet drops. The method is established on a Boolean fault localization technique; the technique requires fewer counters though it only determines whether each link is healthy. This paper extends the Boolean technique so as to deal with traffic volumes with error bounds just by a small number of counters. Along with submodular optimization for the minimum counter placement, we evaluate our method with real network datasets.**

I. Introduction

Traffic Matrix (TM) including packet drops, i.e., where and how much packets are dropped on the path, would be very useful for advanced network engineering; e.g., capacity planning could consider lost traffic in addition to the traffic volume, while traffic engineering could avoid bursty links and failed switch. Conventional TM estimation techniques assume the strict flow conservation, i.e., traffic volumes are unchanged along a path from the origin to the destination [1]. Traffic, however, can be lost due to packet drops in a network.

This paper studies a mathematical model to estimate traffic volumes with their change along a path. The traffic volumes will be determined at each link. Though we can easily get the traffic volumes with their change by counting every path at every link, the number of counters should be minimized to reduce the measurement cost. This paper focuses on the tradeoff between the measurement cost and estimation errors.

Our contributions are summarized as follows: 1) By reformulating the TM estimation for packet drops with Boolean algebra, a new measurability theory that provides the error bounds of the traffic volume is established; 2) A submodular optimization method that minimizes the number of counters is developed based on the measurability theory; 3) Experiments with three real network datasets show that the number of counters in our method is close to the corresponding value of a conventional Boolean technique in most cases, though the conventional technique cannot provide the error bounds and traffic volumes.

II. Formulation

A network is represented by a directed graph, $G = (V, E)$. If there exist some packets forwarded along a path, the path is called a *feasible* path $P \in \mathcal{P}$, where $\mathcal{P}$ is the set of feasible paths in the network. A path is regarded as a set of arcs.

Let C be a set of counters placed in the network. A counter is placed at the tail of directed arc $e_j \in E$ $(j = 1, 2, \ldots, n)$ and maintains the number of packets transmitted into the arc along the associated path. Each counter is specified by the pair of arc and path, e.g., $(e_j, P) \in C$ and $C \subseteq \mathcal{C} = E \times \mathcal{P}$, and the value is denoted by κ_j. Packets are classified to the corresponding counters based on their path using path-oriented packet classification techniques [2]. Let $\tau_j \in \mathbb{R}$ be the number of packets transmitted into e_j along P in a time unit; our model has $\kappa_j = \tau_j$ if a counter is placed at (e_j, P). Let $\hat{\tau}_j$ be an estimated value of τ_j.

The packet drop ratio through arc e_j is denoted by $\ell_j = 1 - \tau_{j+1}/\tau_j \in [0, 1]$. We assume that every arc has *either* a normal state $\ell_j \leq \epsilon$ or an abnormal state $\ell_j \geq \delta$, where $\epsilon < \delta$; it is worth noting that our model works without the strong assumption, $\epsilon \ll \delta$, used in [3]. We assume that every path observes the equal drop ratio for the same abnormal arc, and a single arc failure. Packets are dropped only at arcs, not at vertices.

Our problem is defined as follows: for given G, $\mathcal{P}$, and α,

$$\min_{C \subseteq \mathcal{C}} \{|C| : C \text{ is } \alpha\text{-measurable}\}, \tag{1}$$

where $|C|$ is the number of counters. α-measurable in the above problem is defined as follows: The counter set C is α-measurable if,

$$\forall P \in \mathcal{P}, \forall e_j \in P : \alpha \cdot \tau_j \leq \hat{\tau}_j \leq \frac{1}{\alpha} \cdot \tau_j, \tag{2}$$

where $0 < \alpha \leq 1$.

III. Measurability and Optimization

Separable subpath are consisted by placing counters on paths in our method. A separable subpath $Q = \{e_j, e_{j+1}, \ldots, e_{k-1}\} \subseteq E$ is a part of a feasible path $P = \{e_1, e_2, \ldots, e_l\}$ between a pair of counters $\{(e_j, P), (e_k, P)\}$ and satisfies $(1-\delta) < (1-\epsilon)^{k-j}$. Let $\mathcal{Q} = \{Q_1, Q_2, \ldots, Q_m\}$ be a set of separable subpaths under a counter set C. If $\kappa_k/\kappa_j < 1 - \delta$, we regard P as abnormal.

In our method, an abnormal arc is specified by solving a Boolean equation $\boldsymbol{y} = A(C)\boldsymbol{x}$, where element x_j of $\boldsymbol{x}$ indicates whether $e_j \in E$ is abnormal while y_i of $\boldsymbol{y}$ indicates

Algorithm 1: Counter Placement

Input: A set of feasible paths $\mathcal{P}$ and drop thresholds ϵ, δ.
Output: A set of additional counters X that satisfies $g(X) = g(\mathcal{C})$.

$X \leftarrow \emptyset$;
while $\exists x \in \mathcal{C} : g_0(x|X) > 0$ **do**
  $x^* \leftarrow \arg\max_{x \in \mathcal{C}} g_0(x|X)$;
  $X \leftarrow X \cup \{x^*\}$;
$\mathcal{Q}' \leftarrow$ Separable subpaths of X at $\epsilon = 0$;
while $\exists Q \in \mathcal{Q}' : |Q| - 1 > \lfloor \log_{1-\epsilon}(1-\delta) \rfloor$ **do**
  $X \leftarrow X \cup \{(e_{j+\lfloor \log_{1-\epsilon}(1-\delta)\rfloor}, P)\}$;
  $\mathcal{Q}' \leftarrow$ Separable subpaths of X;
return X;

whether Q_i is abnormal. A *measurement matrix* $A(C) = (a_{ij})$ is defined as the $m \times n$ Boolean matrix of

$$a_{ij} = \begin{cases} 1 & e_j \in Q_i \\ 0 & \text{otherwise} \end{cases}. \tag{3}$$

The j-th column vector is denoted by $\boldsymbol{a}_j$ $(j = 1, 2, \ldots, n)$. A matrix $A(C)$ is *1-independent* if any column vector of $A(C)$ is different from each other and none of them equal to zero; i.e., $\forall j \neq j' : \boldsymbol{a}_j \neq \boldsymbol{a}_{j'}$ and $\forall j : \boldsymbol{a}_j \neq \mathbf{0}$.

For a feasible path $P = \{e_1, e_2, \ldots, e_l\}$, our estimator $\hat{\tau}_j = \kappa_1 \sqrt{(1-\epsilon)^{j-2}}$ if e_j is located on the lower side of the specified abnormal arc, and $\hat{\tau}_j = \kappa_1 \sqrt{(1-\epsilon)^{j-1}}$ otherwise. The error of $\hat{\tau}_j$ is bounded by $\alpha = (1-\epsilon)^{d-2}$ where $d = \max\{|P| : P \in \mathcal{P}\}$. Given the measurement matrix $A(C)$, sufficient conditions of measurability are described by the following theorem.

Theorem 1. *A counter set C is $(1-\epsilon)^{d-2}$-measurable, if the measurement matrix $A(C)$ is 1-independent and every feasible path P has at least one counter on it.*

Based on Theorem 1, we approximately solve the problem (1). To satisfy the condition that every feasible path P has at least one counter on it in Theorem 1, we initially place counters C_0 at first arcs for every P. Additional counters X are optimized based on the coverage function $g(X) = |\{(j,k) : 0 \leq j < k \leq n, \boldsymbol{a}_j \neq \boldsymbol{a}_k\}|$, where $\boldsymbol{a}_j$ is j-th column vector of the measurement matrix $A(C_0 \cup X)$ and $\boldsymbol{a}_0$ is the zero vector $\mathbf{0}$. A function $g(x|X)$ represents the gain of counter $x \in \mathcal{C}$ added to X: $g(x|X) = g(X \cup \{x\}) - g(X)$. The function g_0 is the coverage function for $\epsilon = 0$.

In Algorithm 1, we first solve the problem for $\epsilon = 0$, and then we convert its solution X_0 into a solution X_{ALG} for given ϵ and δ. This is because, when the lower threshold equals to 0, $\epsilon = 0$, the coverage function g_0 becomes a submodular function and a simple greedy algorithm yields an approximate solution with a theoretical guarantee in polynomial-time [4].

IV. Experiments

We perform experiments to evaluate our method using three configuration datasets. The configuration datasets are obtained from Internet2[1], Stanford backbone network [5], and Purdue campus network [6].

TABLE I
NUMBER OF COUNTERS AND ARC-PAIRS FOR $\epsilon = 0$ AND $\delta = 1$

	Internet2	Stanford	Purdue
Initial counters $\lvert C_0 \rvert$	11,159	331	2,985
Additional counters $\lvert X_0 \rvert$	116	65	380
Indistinguishable arc-pairs per all arc-pairs	0 / 9,730	49 / 8,646	0 / 138,075

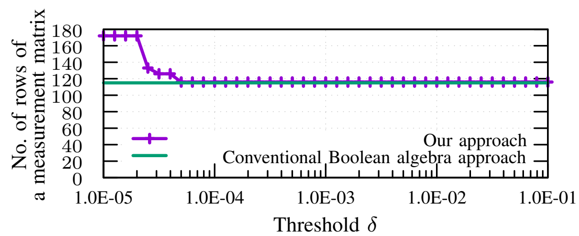

Fig. 1. The number of rows in a measurement matrix.

The optimization results are shown in Table I for $\epsilon = 0$ and $\delta = 1$. An arc pair $(e_i, e_j) \in E^2$ is indistinguishable if the corresponding column vectors $\boldsymbol{a}_i, \boldsymbol{a}_j$ are equal. Though some arc-pairs are indistinguishable only for Stanford due to restrictions of counter placement, most arc-pairs are distinguishable.

The number of rows of measurement matrix (i.e. $|X_{\text{ALG}}|$ in our method) depends on threshold δ; Fig. 1 shows the number of matrix rows for $\epsilon = 10^{-5}$ and $10^{-5} \leq \delta \leq 10^{-1}$ for Internet2. Though our method can provide the error bounds and traffic volumes, for all the datasets, we confirmed that our method almost converges to the conventional Boolean technique [3] for $\delta > 5.0 \times 10^{-5}$

V. Conclusion

This paper proposed a TM estimation method that handles packet drops in a network. With the solid theory about the measurability based on Boolean matrices, we developed an optimization algorithm for the minimum counter set. Experiments showed the great performance with real datasets.

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