On Improving Dynamic Stochastic Routing Algorithms in Overlay Networks

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Abstract— Internet applications are commonly designed and deployed as overlays. Recent studies have shown that overlay nodes may achieve performance gains through intermediate nodes instead of using the default direct Internet path. In this paper, we study a stochastic routing algorithm to determine the detours or relay paths between a pair of end-to-end nodes for performance enhancement by taking the stochastic properties of the overlay links. The main idea and the algorithm features are first illustrated; then, we propose various algorithm improvements by leveraging the actual delay and the expected delay along the path using a stochastic optimization framework. We conducted a simulation study for comparing the proposed stochastic routing algorithm and the conventional routing algorithms. The simulation results show that the proposed stochastic routing algorithm outperforms other algorithms in various network scenarios in reducing packet loss and average delay. With minor variations, the algorithm may be applied for P2P networks and delay-tolerant networks.

Index Terms—relay routing, stochastic optimization, overlay, streaming, network address translator

I. INTRODUCTION

In recent years, various brand new application of the Internet have been reshaping our lives in different networks, such as overlay networks, the delay-tolerant networks, etc. Overlay networks have become the driving wheel to design and deploy emerging Internet applications, such as P2P applications. One of the fundamental problems in overlay networks is to find optimal paths to deliver the content from the source to the destination. Recent studies have shown that overlay nodes may achieve performance gains through appropriate intermediate nodes instead of using the default direct Internet path. In the past decade, a number of overlay routing algorithms have been studied [1]–[3] for performance enhancement or just for establishing connection between two nodes behind network address translators (NAT).

A recent measurement study [4] shows that about 44% Internet users in China are behind NATs, while peers behind NAT are often difficult to establish connections. Some measurement studies [5], [6] continue to show that the triangle inequality may not hold for network delay. Almost 47% detour and relay paths are shorter or equal to the direct paths [6]. This leads to a natural idea of utilizing detours or relay paths to help overlay nodes which cannot establish the direct path blocked by NATs, or the direct path with failures or congestions.

Stochastic shortest path routing is resilient to inaccurate network state information. In this paper, we study the conventional per-hop overlay routing problem in the dynamic and stochastic routing settings by utilizing the statistical properties of overlay links. Unlike conventional dynamic routing, our proposed algorithm requires much less signalling overhead for updating the system states in that it only requires state information exchange locally between one peer and its neighbors, and distribution exchange between nodes in a much larger time scale.

The rest of this paper is organized as follows. In Section II, we formulate the stochastic routing problem. Then, we also analyze the properties of the proposed algorithm and various practical protocol revisions is presented in order to estimate the link state for the better performance. Afterwards we conducted a simulation study for evaluating the performance of the proposed algorithm and serval conventional algorithms including the deterministic shortest path algorithm (DSP), and the minimal hop algorithm (MHP) in Section III. Next, we present the related work of this research in Section IV. Finally, we conclude this paper and present future work of applying stochastic routing in delay tolerant networks in Section V.

II. PROBLEM FORMULATION

The overlay routing follows the evolutive approach for improving routing performance without changing the current underlaying routing algorithms. In a P2P network, the quality of overlay links between peers varies in time due to cross traffic competing for bandwidth along the path. It was reported that Internet paths have stationary delay/loss performance in the hour scale [7]. Unlike the traditional network models, peer churn may result in the connection between peers changing frequently, and this may even lead to the need of adjusting the P2P network topology [8]. When some errors happened between peers, the Internet has the flexibility to find relay paths to deliver the data. One overlay link may consists of dozens of physical links. When a node makes an overlay routing decision, its information about the overlay links, especially those remote overlay links, is often not updated and hence of uncertainty. In this paper, we propose a stochastic optimization framework by utilizing the accurate immediate overlay link state and the stochastic link state of remote overlay links.

A. Stochastic Delay Computation

Consider a particular path \( p \) from source \( S \) to destination \( D \) in the overlay network as shown in Fig.1. We assume that \( S \) and \( D \) cannot setup direct connection between each other due to NAT blocking; nevertheless, they can utilize
some relay nodes to forward packets similar to the NAT traversal in Skype. Fig. 1(a) illustrates an overlay routing example using 2 relay nodes, in which $R_1$ and $R_2$ are two relay nodes on the forwarding routing path. In this case the delay from the source to the destination can be calculated as $T_{sd} = T_{sr1} + T_{r2r} + T_{rd}$. Assume source $S$ is able to measure the delay $T_{sr1}$ accurately, while it is not able to obtain the accurate delay of $T_{r1r2}$ and $T_{rd}$. In this case, the routing algorithm is difficult to find a good relay path, because of lacking of the accurate delay information of remote links from the intermediate nodes to the destination.

![Image](a) Normal overlay routing  (b) Expected overlay routing

Fig. 1. The overlay routing examples with relay nodes

We use the expected delay of the remote overlay links to quantify their link state. Source $S$ can measure the delay of the direct overlay link $T_{sr1}$, while the delay of those remote links cannot be measured at the source, e.g., $T_{rd}$. Nevertheless, we assume that the statistical properties of remote links can obtained and updated by other nodes to the source. Thus, the delay of remote links can be approximated as the expected delay computed from the statistics. Hence, as shown in Fig.1(b), the total path delay starting from $S$ to $D$ can be decomposed into two components: $S \rightarrow R_1$ and $R_1 \rightarrow D$. The expected delay from the relay node to the destination is simplified as $E_{r1}$. Then, the total path delay is computed as $T_{sd} = T_{sr1} + E_{r1}$. The optimization goal is to select the best relay $R_1$ so as to minimize the total path delay $T_{sd}$.

To assist the discussions, we first provide some notations, then show the proposed optimization model. Consider an overlay network denoted by $G = (\mathcal{N}, \mathcal{A})$, where $\mathcal{N}$ is the set of overlay nodes and $\mathcal{A}$ is the set of overlay links. Let $S(j)$ be the set of all successors of node $j$ and $E_j$ be the expected link delay from the current successor node $j$ to the destination node $D$. $S(s)$ represents the neighbor set of the source node $S$. Denote $T_{sd}$ as the total path delay from the source $S$ to the destination $D$, and the relay routing problem is formulated as follows:

$$T_{sd} = \arg \min_{j \in S(s)} \{ D_{sj} + E_j \}. \quad (1)$$

B. Stochastic Routing Framework

The basic idea of the classic packet routing follows the store-and-forward fashion: every node only needs to examine the destination address in the packet header and select a proper outgoing interface. Note that the selection of the “proper” outgoing interface is essentially based on the information of network hops. Routing algorithms in wired networks often assume that link information is accurate and updated between nodes if remote links change. In an overlay, one overlay link may consists of a number of physical links. It is time-consuming and overhead-intensive to measure and update link states in order to maintain an accurate network traffic map. Nevertheless, link states often have some stationary stochastic properties, such as diurnal behaviors or stationary at the hour-level granularity. These stochastic link properties can be used to reduce the measurement overhead and network update traffic in a stochastic routing framework.

In the proposed stochastic routing framework, we decompose the computation of the path delay into two components, deterministic delay of immediate links plus the statistical delay of the remote links, while the latter can be computed recursively using polynomial-time algorithm. We use two delay parameters to characterize link delays to facilitate the algorithm design: 1) the delay at one time observation; 2) the link delay distribution. For example, given a link, there exist multiple value pairs for this two-parameter group.

Define

$$\mathcal{R}_{ij} = \{1, 2, \ldots, r_{ij}\} = \text{the set of all possible delay states of link } (i,j);$$

$$d_{ij}^r = \text{actual value of } D_{ij} \text{ in delay state } r, r \in \mathcal{R}_{ij};$$

$$p_{ij}^r = \text{probability that delay } r \text{ occurs.}$$

For any link $(i,j)$, node $i$ maintains a delay value set associated with different probabilities. Note that $\sum_{k=1}^{r} p_{ij}^k = 1$. As far as each link is concerned, the algorithm uses the discrete values to approximate the link delay distribution, thus the sum of the probabilities of delay states of the link is equal to 1. Later this paper will also discuss how to approximate the average delay using a time-moving average technique.

$$E_{ij} = \sum_{k=1}^{n} (p_{ij}^k \times d_{ij}^r),$$

$$\text{where } \sum_{k=1}^{n} p_{ij}^k = 1, n = \max(\mathcal{R}_{ij}). \quad (2)$$

C. Stochastic Single-path Routing

Based on Equation (1), a shortest stochastic routing path can be computed by solving Equation (3). The optimization goal of the proposed stochastic routing problem is to find the minimal path delay of the local delay and the expected delay of remote links towards the destination. The local delay can be obtained using measurement, while the delay distribution can be estimated by historical measurements by remote nodes. In Equation (3), $D_{ij}^o$ denotes the current delay of link $(i,j)$ at the observation and $E_{ij}^o$ denotes the minimal expected delay from node $j$ to the destination at the current observation. $T_{ij}$ is the minimized path delay from node $i$ to node $j$ using relays.

$$T_{ij} = \arg \min_{j \in S(i)} \{ D_{ij}^o + E_{ij}^o \}. \quad (3)$$

We develop a recursive stochastic routing algorithm to find a relay path with the minimal expected delay. Let $E_{ij}^o$ be the expected delay of the stochastic shortest path from the relay $r$ to the destination and $S(r)$ be the set of all successor relays which the source can select. The relay $r'$ selected by the stochastic routing algorithm satisfies the condition described in Equation (4).
\[ r' = \arg \min_{r \in S(r)} \{D^0_{rd} + E^r_v\}. \quad (4) \]

### D. Stochastic Multi-path Routing

The stochastic routing can also be extended for selecting optimal multiple paths to achieve path diversity and to reduce the loss performance in streaming applications if applying coding techniques jointly. Multi-path routing utilizes the potential usable links and avoids the possible unavailability of the shortest path. In some cases, multi-path routing is able to achieve the load balancing for the whole network. A stochastic path specifies a path from source to destination at any delay observations of the whole network. Two stochastic paths are distinct if for each possible observation of the link delays of the whole network, these two paths differ for at least one link. The stochastic shortest path is defined as the path that has the minimum expected delay. The \( k \)-th stochastic shortest path is the one that has the minimum expected delay among all stochastic paths that are distinct from the first \( k - 1 \) stochastic paths. Let \( \omega_i \) be the outcome (observation) of the delays of all links out of node \( i \) and \( \Omega_i \) be the set of all these possible outcomes. Denote \( e_i^k \) as the expected delay of the \( k \)-th stochastic shortest path from node \( i \) to destination \( n \). The \( K \) stochastic shortest path problem is then formulated in Equations (5).

**Definition 1:**

\[ e_n^k = \begin{cases} 0, & \text{if } k = 1; \\ \infty, & \text{otherwise.} \end{cases} \]

\[ e_i^k = E\left[ \min^k \{D_{ij}(\omega_i) + e_j^k : \ell = 1, 2, \ldots, k, j \in S(i) \} \right], \quad k = 1, 2, \ldots, K, i \in N \setminus \{n\}, \quad (5) \]

where \( \min^k \) is the \( k \)-th smallest value of a set.

### E. Dynamic Routing Information Update

Although the stochastic routing algorithm is to find the path based on the statistical link delay, we still need the routing update mechanism for the algorithm in order to approach the link delay more accurately using Equation (2). The probability distribution function of link delays can be measured between nodes. [9] assumes that the distribution function is known predically, and doesn’t update the distribution function in time when the path states changes.

For a practical implementation, we use the historical delays measurements to formulate an end-to-end delay model. We assume the probability distributions of the link delays are all discretized. Then we utilize the delay measurements to approximate the distribution, since a continuous probability distribution function can be approximated with a discrete counterpart with sufficient accuracy. The actual delay update process can be conducted using BGP-like messaging. The update process forwards the expected delays of the node’s neighbor to the destination. The simplest update mechanism can be designed as a moving-average of historical measurements in Equation (6).

\[ E_{ij} = \sum_{k=1}^{n} (p_{ij}^k \times d_{ij}^k) \]

\[ = p_{ij}^1 \times D_{ij}^1 + p_{ij}^2 \times D_{ij}^2 + \cdots + p_{ij}^k \times D_{ij}^k \]

\[ = \alpha \times D_{ij}^1 + (1 - \alpha) \sum_{k=1}^{n} (p_{ij}^k \times d_{ij}^k) \quad (6) \]

Because the current link state is much closer to the most recent observation or measured delay, \( D_{ij}^1 \) and its corresponding distribution \( p_{ij}^1 \) may greatly affect the final results of the stochastic algorithm. In order to distinguish this distribution value, we substitute \( p_{ij}^1 \) with \( \alpha \). Hence, Equation (2) is now changed to Equation (6). We will examine the impact of the most recent delay and the distribution on the stochastic algorithm, and study the trade-off between more recent measurements and the historical delays.

### III. Evaluation

#### A. Simulation Setup

In this section, we present the simulation settings with different network topologies. We evaluate the original stochastic routing and the enhanced dynamic stochastic routing in two overlay network topologies as shown in Fig. 2. In Fig. 2(a), traffic are sent from node \( S \) to node \( D \) via only one relay node. There are 5 relay nodes between source \( S \) and destination \( D \). In Fig. 2(b), traffic will traverse two relay nodes before reaching the destination \( D \). In this network, there are 10 relay nodes arranged in two columns between the source-destination node pair. [6] shows that the nearly 80% performance gained from the relay paths needs only 2 relays at most. We consider these two topologies as typical overlay network scenarios in simulations. All these simulation models were constructed based on SimLib 2.6 [10], developed at IKR, University of Stuttgart.

![Fig. 2. The overlay topology used in simulations.](image)

#### B. Loss and Delay Model

The links between nodes are logical links in overlay networks, quite different from the direct physical links. One logical link may consist of many physical hops; therefore, these logical links in overlay networks may exhibit different loss and delay characteristics from the physical links. An accurate model for packet loss over the Internet is quite complex. Here, we use a two-state Markov chain model [11], known as Gilbert model to approximate the packet loss on the overlay links.
Similar to the loss model, the delay characteristics of overlay links are difficult to capture accurately. [12] showed that the delay distribution can be approximated by a shifted Gamma for the end-to-end paths. Measurement is commonly practiced for overlay applications. Usually only the most recent delay samples or long term moment statistics are used in routing decisions. We now use the historical delay samples to approximate the delay distribution. In order to evaluate the stochastic routing algorithm under different network environments, we applied three packet delay distribution models of overlay links: Uniform Distribution, Gaussian Distribution, and Gamma Distribution. For the uniform and Gamma distribution, we assume a delay range [5ms, 320ms]. For the Gamma distribution, we restrict the shape(α) and scale(β) parameters’ range used in [12].

C. Simulation Results

Consider a streaming application which generates packets from source S to destination D. The application tries to setup an end-to-end connection between S and D using relays. We also assume that these overlay links are independent. When the packets are delivered using multiple overlay paths, for simplicity, the packets will traverse along different paths in a round-robin fashion. Using the multiple overlay paths, network capacity is better utilized and load balancing is achieved.

1) Stochastic Routing v.s. Traditional Routing: We compared the K-th Dynamic Stochastic Shortest Path (DKSSP) routing algorithm with two traditional algorithms including the Deterministic Shortest Path (DSP) and the minimal hop (MHP) in terms of the average delay and loss probability. As shown in Fig.3, DKSSP has significantly smaller average delays than DSP and MHP. No matter in one-tier relay or two-tier relay scenarios, DKSSP has improve nearly 20% - 40% delay performance than these two traditional algorithms. When using the K-th multi-path stochastic shortest path, the average delay of multi-path routing is slightly worse than that of single shortest path routing. Because the algorithm selects different shortest path, once a path is selected, it will be excluded from the set of the candidate path.

![Graphs showing average delay performance](image-url)

Fig. 3. Average delay performance

We also examined the loss performance with compared with these three algorithms. In Fig.4, the multi-path routing jointly with Forward-Error-Correction codes (FEC) [11] reduces the loss probability significantly. The results show that the KSSP with FEC can achieve more benefits than the other two traditional algorithms: DSP and MHP. Fig.5 depicts the average loss performance comparison of the KSSP with/without FEC. The results show that KSSP with FEC can greatly decrease the packet loss than its original version. The results of these figures show that KSSP can achieve better performances on the link average delay and packet loss rate.

![Graphs showing average loss performance](image-url)

Fig. 4. Average loss performance with FEC

![Graphs showing average delay performance](image-url)

Fig. 5. Average loss performance without FEC

2) Static v.s. Dynamic Stochastic Routing: In this section, we present the comparison results between the static stochastic routing (KSSP) and the dynamic stochastic routing (DKSSP). The difference is that the dynamic stochastic routing can periodically update the link local delay and non-local delays using the routing messages. In Fig.6, DKSSP can gain 5% - 10% delay performance through one-hop relay path from KSSP. However, DKSSP has a very slight increase of average delay compared with KSSP. Note that the dynamic stochastic routing algorithm is based on two factors: the most recent delay range values through statistics and the delay distribution. In these comparison experiments, we assign the weight of the delay distribution to a fixed value and only use the dynamic routing delay information. Hence, the gain from the DKSSP is limited, the following simulations will show the improved performance with the moving average between latest delay and the historical delay measurements.

![Graphs showing average delay performance](image-url)

Fig. 6. Average delay performance
In order to show the impact of the delay distribution, a set of experiments have been conducted under different combinations of the delay information and $\alpha$ values. Fig. 8 shows that the increase of the recent delay distribution improve the delay performance combined with routing update mechanism with the Dynamic Stochastic Routing algorithm (DKSSP). Note that the minimal hop routing (MHP) only considers the minimal hops, which do not consider the link delay at all; hence, the simulation results vary greatly in terms of the average delay. We provide a comparisons between DKSSP with KDSP and KSSP. Fig.9 and Fig.10 show that DKSSP have better average delay performance than KDSP and KSSP. In Fig.10, we find that the delay distribution impacts the simulation results greatly. With increasing the weight of the distribution from $\alpha = 0.1$ to $\alpha = 0.9$, we observe that the average delay decrease gradually. The results also show even though we are not able to approximate the delay distribution accurately through routing updates, the algorithm can still utilize the most recent delays with the over weighted delay distribution to achieve better performance.

IV. RELATED WORK

Routing is a classic networking problem to find a path considering different routing metrics, e.g. delay, packet loss, bandwidth, connectivity and so on. We outline a few typical work most related to this paper.

Savage et. al. [13] was the first to raise the fundamental question: How to find a good Internet path from considering Round-Trip-Time(RTT), packet loss rate, and bandwidth. They showed that there usually exists an alternate routing path existing in the network with lower RTT compared with the default direct routing path. [14] further showed that by compromising the underlay network delay, packet loss rate etc., the routes can decide a good path for transmitting data from the source to the destination. The Resilient Overlay Network (RON) [15] was an architecture initiative for application-layer overlay routing and developed an one-hop overlay routing algorithm to gain the most of performance in RTT, packet loss rate and TCP throughput. Recent work for alternative Internet paths can be found in [6].

[9] also proposed to construct a stochastic framework to formulate the routing problem in P2P networks. The authors studied a new class of stochastic shortest path and the expected delays in the overlay networks. However, a comprehensive evaluation is yet to be conducted to demonstrate the advantages and disadvantages of stochastic routing. Furthermore, two issues remain to be answered: 1) how to approximate the link delay distribution using historical delay measurements with sufficient accuracy; 2) the algorithm requires dynamic link information updates for practical implementation.

[16] formulated the relay selection problem as a NP-hard optimization problem, namely, the Overlay Routing Resource Allocation(ORRA) problem. This paper proposed a non-trivial approximation algorithm to solve the problem sub-optimally as
to find a minimal set of overlay nodes such that the required routing properties are satisfied. The results show that a relative small number of less than 100 relay servers are sufficient to find shorter paths in the two practical scenarios, BGP routing and TCP improvement.

This paper presents an extensive study of stochastic routing on link delay and packet loss rate under different network conditions. We improve the dynamic link state updates in the stochastic network settings so that the algorithm can capture the link delay samples of local links and more accurately approximate the delay distributions of remote overlay links.

V. CONCLUSION

In this paper, we conduct a performance evaluation of stochastic routing using extensive simulations on two major metrics: delay and packet loss. Based on our simulation results, we find that the stochastic routing is able to achieve significant performance gain in link delay and packet loss rate against the traditional routing. The proposed stochastic routing algorithm reduces 20% – 40% in delay than the deterministic shortest path routing and the minimal hop routing. This algorithm can also been integrated with FEC for achieving better resilient delivery for reducing nearly 50% packet loss rate than two other algorithms.

The stochastic routing utilizes the statistical properties of overlay links, while these distribution statistics vary at a much longer time scale; hence, the update operations occur with much less frequency so as to lead to minimal update traffic. For a practical implementation, the dynamic stochastic routing utilizes the historical link updates to approximate the link statistics in delay values and delay distributions. In order to demonstrate the improvement of the updated approach, we compared the original algorithm and the improved version. The simulation results have shown that the dynamic stochastic outperforms the original algorithm in reducing link delay and packet loss. Using the different delay distributions, the more recent link delay distribution achieves more delay and packet loss gain. It is also feasible by leveraging the recent delay history and the delay distribution to approximate the link state in stochastic routing.

Note that the experiment settings in this paper are tailored to simulate the P2P scenarios. The proposed stochastic routing algorithm is also applicable for the delay-tolerant network (DTN). In DTN, an end-to-end path may be unavailable at some times; routing is performed to achieve ultimate end-to-end delivery by employing cached storage at the intermediate nodes. This indicates that the traditional dynamic routing algorithms may not achieve desired performance in DTN. However, the stochastic routing is constructed only based on the statistical information of overlay links; thus, it is resilient to inaccurate link state information. This brings forth potential applications of stochastic routing in DTN applications.

REFERENCES