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オーバレイネットワークにおける局所的な情報交換に基づく分散型計測手法

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あらまし オーバレイネットワークサービスの品質と効率を向上させるためには，アンダーレイネットワークの性能をリアルタイムかつ高精度に計測する必要がある．この時，計測頻度を高めることにより，計測精度を向上することができるが，計測する複数のパスの経路が重複している場合には，重複箇所において計測衝突が発生し，計測負荷の増大や計測精度の低下が問題となる．本稿では，計測衝突を軽減し，計測精度を向上する分散型計測手法を提案する．提案手法においては，オーバヘッドおよび計測衝突を軽減するために計測頻度を削減する一方で，オーバレイパスの経路情報と計測結果に関して必要最低限の情報交換を行い，統計的手法によって計測精度を保つ．性能評価の結果，計測オーバヘッドと情報交換オーバヘッドの合計が同等である場合において，提案手法を用いることで計測結果の相対誤差を既存手法に比べて 50% 以上改善できることを示す．さらに，情報交換を行うことが計測を行うことより計測精度の向上に役立つことを明らかにする．

キーワード オーバレイネットワーク，ネットワーク計測，計測衝突，経路制御，統計処理

A distributed and conflict-aware measurement method using local information exchange in overlay networks

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Abstract Network resource information, including available bandwidth, propagation delay and packet loss ratio, should be obtained by measurements for maintaining effectiveness of overlay network services. Although measurement accuracy can be enhanced by frequent measurements, performing measurements with high frequency can cause measurement conflict problem, that increases the network load and degrades measurement accuracy. In this report, we propose a distributed and conflict-aware measurement method which can reduce measurement conflicts and obtain high measurement accuracy. The main idea is that overlay nodes exchanges the route information and measurement results only with neighboring overlay nodes, while decreasing the measurement frequency. Simulation results show that the relative error of measurement results of our method is less than half of that of an existing method when the total measurement overhead of both methods are equal. We also confirm that exchanging of measurement results contributes more to the enhancement of measurement accuracy than performing measurements.

Key words Overlay networks, network measurement, measurement conflict, information exchange, statistical method

1. Introduction

Overlay networks enable network services to overcome the path outages and periods of degraded performance of the IP networks. In overlay networks, the overlay nodes are often installed on end hosts as an application program. In this case, routing and traffic control at the overlay detecting level are conducted at the end hosts, and such controls cannot be activated inside the network. On the other hand, the overlay routing inside the network becomes possible by installing overlay nodes on the routers in the network. In this report, to realize efficient routing control by overlay networks, we consider an overlay network in which the overlay nodes are deployed on the routers.

To maintain and improve the performance of network service, an overlay network should obtain the network resource information of the underlay network, including available bandwidth, propagation delay, and packet loss ratio. These metrics should be measured frequently to obtain high measurement accuracy. RON [1] is one early-stage instance that measures all paths among overlay nodes. The measurement overhead becomes $O(n^2)$, where n is the number of overlay nodes. Therefore, [2] pointed out that the number of overlay nodes that can be applied is up to around fifty. Many solutions have been proposed to reduce measurement overhead [3–7]. However, these methods have shortcomings in terms of measurement accuracy [3] or available measurement metrics [5, 6].

Measurement accuracy is affected not only by the way measurements are performed but also by the overlap of underlay paths among overlay nodes. Concurrent measurement tasks of overlapping paths compete on the common links for network resources (e.g., processing power at routers and link bandwidth), causing high load on the common links and additional error in the measurement results. [8] addresses this problem and proposes a method that schedules the timing of the measurement tasks of the overlay paths so that measurement conflicts can be avoided completely. However, the measurement frequency in this method is limited because of the heuristic behavior of the proposed scheduling algorithms [9]. Moreover, the methods in [3, 4, 7, 8] require a master node to aggregate the complete topology information of the underlay (IP) network, decide measurement timings, and give instructions to each overlay node. Therefore, the amount of time and network traffic for the aggregation of topology information and instructions are large, and the performance of overlay networks decreases when changes occur in the underlay or overlay networks.

In this report, we propose a distributed measurement method that can reduce measurement conflicts and obtain high measurement accuracy. In our proposed method, each overlay node exchanges route information with its neighboring overlay nodes to detect the overlapping paths. Overlapping paths with the same source node are measured sequentially to completely avoid measurement conflicts. Overlapping paths having different source nodes are randomly measured to reduce measurement conflicts. The overlay node then exchanges the measurement results with its neighboring overlay nodes to statistically improve measurement accuracy. Our method can also lower the measurement frequencies to reduce overhead and measurement conflicts.

We make the following contributions in this report:

- We propose two algorithms for detecting the overlapping paths that do not require complete topology knowledge of the IP network at each node.
- We propose a method for determining the measurement frequencies and timings of the overlapping paths to reduce measurement conflicts.

We evaluate our method and compare it with the method in [8] by simulations with both generated and real Internet topologies. From the simulation results, we reach the following conclusions:

- Our method detects more than 90% of the overlapping paths with less than 30% of the information exchanges of the full-mesh method.
- When the overheads of both methods are equal, the relative error of the measurement results of our method is less than half of the method in [8].

2. Detecting overlapping paths

2.1 Network model and definitions

We consider a network with m routers, denoted by R_i ($i = 1, ..., m$). We denote the underlay path between two routers R_i and R_j as R_iR_j. If two different paths R_iR_j and R_sR_t share at least one link, we say that R_iR_j and R_sR_t overlap with each other, or R_iR_j (R_sR_t) is an *overlapping path* of R_sR_t (R_iR_j). Suppose that there are n ($n \leqq m$) overlay nodes deployed on n routers. Density d of the overlay nodes is defined as the ratio of the number of overlay nodes to the number of routers, i.e., $d = n/m$. We denote the overlay nodes as O_i ($i = 1, ..., n$) and call the path between two overlay nodes an *overlay path*. For overlay path O_iO_j, O_i is the *source node*, and O_j is the *destination node* of the overlay path.

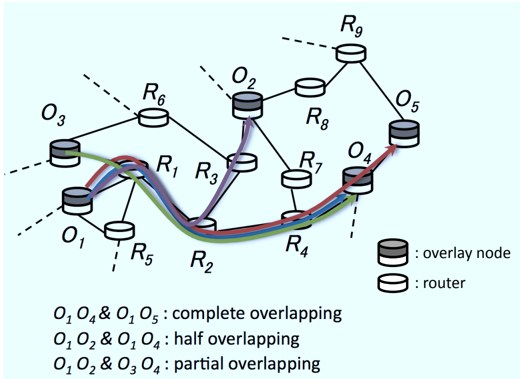


Fig. 1 Classification of path overlapping

Figure 1 shows a classification of the overlapping state of overlay paths. In this report, we classify overlapping states into the following three types:

- *Complete overlapping*: One overlay path completely includes another overlay path.
- *Half overlapping*: Two overlay paths share a route from the source node to a router that is not an overlay node.
- *Partial overlapping*: Two overlay paths share a route that does not include the source node.

For example, in Fig. 1, path O_1O_4 is a complete overlapping path of O_1O_5. Paths O_1O_2 and O_1O_4 have a half overlapping relation. Path O_1O_2 is a partial overlapping path of O_3O_4.

2.2 Methods for detecting complete and half overlapping paths

Complete overlapping and half overlapping can be detected by the source node of the overlay path using `traceroute`-like tools, as described in [10]. For example, in Fig. 1, when overlay node O_1 issues `traceroute` to O_4 and O_5, complete overlapping of paths O_1O_4 and O_1O_5 can be detected. Similarly, the shared route from O_1 to router R_2 by paths O_1O_2 and O_1O_4 can be detected when O_1 issues `traceroute` to O_2 and O_4.

2.3 Method for detecting partial overlapping paths

2.3.1 Detecting algorithms

Partial overlapping cannot be precisely detected only by `traceroute`-like tools, because the source nodes of the partial overlapping paths are different. Therefore, in this subsection, we propose the following method for detecting partial overlapping paths.

We demonstrate how an overlay node O_i detects the partial overlapping paths. We denote the set of overlay paths whose source nodes are O_i, which contain at least two links and do not completely include other overlay paths as $\mathcal{S}_{O_i}$. We also denote the set of overlay paths whose destination nodes are O_i, which contain at least two links and do not completely include other overlay paths as $\mathcal{D}_{O_i}$. Note that we exclude one-link paths when defining $\mathcal{S}_{O_i}$ and $\mathcal{D}_{O_i}$ since they do not have partial overlapping paths. Also, we do not directly measure the paths that completely include other overlay paths, as described in Subsection 3.1.1. Our method consists of the following two algorithms that detect the partial overlapping paths of each path in $\mathcal{S}_{O_i}$ and $\mathcal{D}_{O_i}$, respectively.

- Algorithm 1:

O_i detects the partial overlapping paths of each path O_iO_j in $\mathcal{S}_{O_i}$ as follows.

(1) O_i finds the candidates of the partial overlapping

paths of O_iO_j by utilizing the information of its half overlapping paths.

In detail, when O_iO_s and O_iO_t are half overlapping paths of O_iO_j and when the length of the overlapping part of O_iO_j and O_iO_s is smaller than the length of the overlapping part of O_iO_j and O_iO_t, we infer that O_sO_t is a candidate of the partial overlapping path of O_iO_j.

(2) O_i exchanges path information with the source nodes of the candidates to decide the overlapping states between O_iO_j and the candidates.

In detail, O_i exchanges path information with O_s to determine whether O_iO_j and O_sO_t actually have a partial overlapping relation. Furthermore, when receiving path information from other nodes, O_i may find new candidates of the partial overlapping paths. In that case, O_i repeats the information exchange and the decisions of the overlapping states.

We use Fig. 1 to explain how Algorithm 1 works for path O_1O_2. Set $\mathcal{S}_{O_1}$ includes O_1O_2, O_1O_3, and O_1O_4 and does not include O_1O_5 because it completely contains O_1O_4. We infer that path O_3O_4 is a partial overlapping path of O_1O_2, because the length of the overlapping part of O_1O_2 and O_1O_3 is smaller than the length of the overlapping part of O_1O_2 and O_1O_4. O_1 then exchanges path information with O_3 to confirm whether O_1O_2 and O_3O_4 actually have a partial overlapping relation.

- Algorithm 2:

O_i exchanges the information of the paths in $\mathcal{D}_{O_i}$ with their source nodes to detect their partial overlapping paths as follows.

(1) O_i receives information of each path in $\mathcal{D}_{O_i}$ from the source node (referred to as O_s) of the path.

(2) O_i detects the partial overlapping paths of each path O_sO_i in $\mathcal{D}_{O_i}$ and sends information of these paths to O_s.

We also use Fig. 1 to explain how Algorithm 2 works for path O_2O_4. Set $\mathcal{D}_{O_4}$ includes O_1O_4, O_2O_4, and O_3O_4 and does not include O_5O_4 because it contains only one link. First, O_4 receives the information of paths O_1O_4, O_2O_4, and O_3O_4 from O_1, O_2, and O_3, respectively. O_4 then detects that O_1O_4, O_2O_4, and O_3O_4 are in a partial overlapping relation and sends the information of O_1O_4 and O_3O_4 to O_2.

2. 3. 2 Evaluation of detecting algorithms

We evaluate our proposed algorithms for detecting partial overlapping paths by simulations with two metrics, defined as follows:

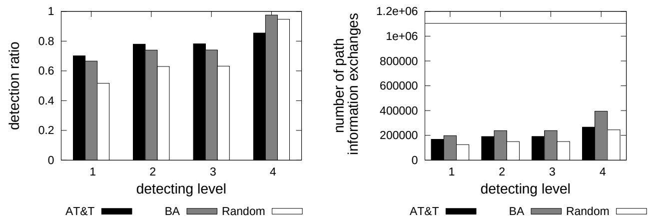
- *detection ratio*: ratio of the number of detected partial overlapping paths to the actual number of partial overlapping paths.
- *number of path information exchanges*: number of times that the information of overlay path was exchanged among the overlay nodes.

Algorithm 1 includes iterations for information exchange and the decision of the overlapping states. When the number of iterations increases the detection ratio is enhanced, while the overhead of the information exchange among the overlay nodes also increases. In addition, since Algorithms 1 and 2 can be conducted independently, we set the following four detecting levels to conduct Algorithms 1 and 2 to investigate the trade-off relationships between the detection ratio and the information exchange overhead.

- detecting level 1: run Algorithm 1 with one iteration.
- detecting level 2: run Algorithm 1 with two iterations.
- detecting level 3: run Algorithm 1 completely.
- detecting level 4: run Algorithms 1 and 2 completely.

For the underlay network topology, we used the AT&T topology obtained from [11]. We also utilized generated topologies based on BA [12] and random models [13]. We generated ten topologies for each model using the BRITE topology generator [14]. All topologies have 523 nodes and 1304 links. We set the density of the overlay nodes to 0.2 and randomly chose them. For averaging the results, the choice of the overlay nodes was taken 100 times for the AT&T topology and ten times for each topology of the BA and random models.

We compared our method with the full-mesh method when evaluating the number of path information exchanges. In the full-mesh method, each overlay node sends information of all



(a) (b)

Fig. 2 Average detection ratio of partial overlapping paths and average number of path information exchanges

overlay paths departing from it to all other overlay nodes. When the number of overlay nodes is n, the number of path information exchanges of the full-mesh method is $n(n-1)^2$, which becomes 1,103,336 in the evaluation results.

The average detection ratio of the partial overlapping paths and the average number of path information exchanges are shown in Fig. 2. The black, gray and white bars show the results of the AT&T topology, the BA topologies, and random topologies, respectively. The line in Fig. 2(b) represents the number of path information exchanges of the full-mesh method. As shown in these figures, our method needs only 1/6 and 1/3 of the path information exchanges to detect about 60% and 90% of the partial overlapping paths at detecting levels 1 and 4, respectively. The results of detecting levels 2 and 3 are very close, meaning that we only need to run two iterations of the exchange loop of Algorithm 1.

3. Measurement method for overlay paths

In this section, we propose a method for reducing the measurement conflicts based on the status of the path overlapping detected by the method in Sect. 2. First, note that if an overlay path has no overlapping paths, it is unnecessary to consider a method for reducing measurement conflicts. Therefore, we are only concerned with the case of overlay path that has overlapping paths. We consider the following two cases of overlapping states:

(1) When the overlay path completely includes other overlay paths, it is not measured directly.

(2) When the overlay path does not include other overlay paths, we adjust the frequency and timing of the measurements to reduce the measurement conflicts.

The detailed mechanisms for the above two cases are described in Subsects. 3. 1. 1 and 3. 1. 2, respectively. In Subsect. 3. 2, we propose a statistical method for improving the accuracy of the measurement results.

3. 1 Reducing measurement conflicts

3. 1. 1 Complete overlapping

In this case, the overlay path that includes the other overlay paths is not measured directly. Instead, the measurement result is estimated based on the measurement results of the overlay paths included in it.

We use Fig. 3 to explain this method. As shown in this figure, path O_iO_w completely includes path O_iO_j. When O_i issues `traceroute` to O_w, the `traceroute` packet goes through O_j, which learns that it is on path O_iO_w. O_j then measures path O_jO_w and transmits the result to O_i, which also learns that O_j is on path O_iO_w, based on the `traceroute` result. Then O_i does not directly measure path O_iO_w; it only measures path O_iO_j. O_i estimates the measurement result of path O_iO_w from the measurement result of path O_iO_j and that of path O_jO_w received from O_j. See [10] for details.

3. 1. 2 Half and partial overlapping

We explain the proposed method by describing the detailed behavior for overlay path O_iO_j shown in Fig. 3. Here, we assume that O_iO_j has $(G-1)$ half overlapping paths $(G \geqq 1)$. We denote path O_iO_j as path 1, and each of its half overlapping paths as path p $(2 \leqq p \leqq G)$. Furthermore, we assume that, with the method described in Sect. 2. to detect partial overlapping paths, path p $(1 \leqq p \leqq G)$ has $(K_p - 1)$ partial overlapping paths $(K_p \geqq 1)$.

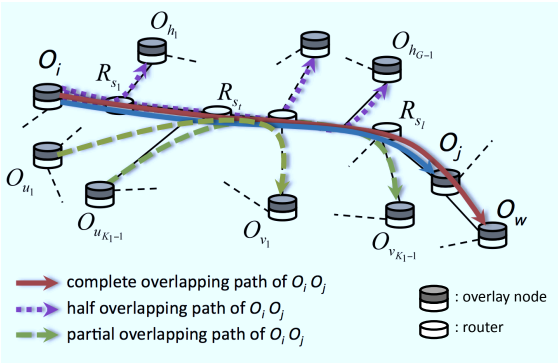


Fig. 3 Example for explaining the proposed measurement method

Overlay node O_i can avoid the measurement conflicts between half overlapping paths 1, 2, ... and G simply by measuring them sequentially. On the other hand, because the source nodes of the partial overlapping paths of path p are different, measurement conflicts between them cannot be avoided completely. Therefore, we propose a technique that combines a sequential measurement for half overlapping paths and a random measurement for partial overlapping paths. We define the *measurement frequency* as follows. We assume that the time required for each measurement task is identical for all overlay paths and denote it as τ. We also assume that the measurement results of path p are aggregated in the time duration of T_p ($T_p \geqq \tau$). We call T_p an *aggregation period*. When a path is measured q ($q \leqq T_p/\tau$) times at an aggregation period, its measurement frequency at that aggregation period is defined as $f_p = q\tau/T_p$.

We introduce β_p as a value that reflects the dispersion of the measurement results of path p at an aggregation period. Note that the method to determine β_p is beyond the scope of this report. β_p can be calculated based on the statistics of the measurement results or using the method in [6]. We set measurement frequency f_p proportional to β_p for all paths, i.e., $f_1/\beta_1 = f_2/\beta_2 = ... = f_G/\beta_G$. To avoid measurement conflicts between half overlapping paths, the sum of their measurement frequencies should be equal to or less than one, i.e., $\sum_{p=1}^{G} f_p \leqq 1$. So we have $f_p \leqq \beta_p/(\sum_{s=1}^{G} \beta_s)$.

To reduce the probability of measurement conflicts between path p and its $(K_p - 1)$ partial overlapping paths, we set the measurement frequency of path p to a value equal to or less than $1/K_p$, i.e., $f_p \leqq 1/K_p$. In addition, we keep the measurement frequencies as large as possible to obtain as many measurement results as possible. Therefor, the measurement frequency of path p is decided based on the following equation:

$$f_p \quad = \quad \min\{\beta_p/(\sum_{s=1}^{G} \beta_s), 1/K_p\}. \qquad (1)$$

Next, we explain our method for randomly deciding the measurement timings of path p so that the probability that the measurement of path p is carried out becomes f_p. We define a *measurement cycle* for the measurements of paths 1, 2, ... and G. We also divide the measurement cycle into multiple *measurement time slots*, each of which is assigned to the measurement of each path. We consider a scheme for allocating the measurement timings of paths p to these measurement time slots as follows.

When a path is measured at one measurement time slot of the measurement cycle, the probability that the measurement of the path is carried out becomes $1/G$. Therefore, we compare f_p with $1/G$ when considering the measurement timings of path p. We assume that $f_1 \geqq f_2 \geqq ... \geqq f_G$ without loss of generality. For convenience, we define dummy value $f_0 = 1$. Since $\sum_{s=1}^{G} f_s \leqq 1$, $0 \leqq l < G$ exists, such that $f_0 \geqq ... \geqq f_l \geqq 1/G \geqq f_{l+1} \geqq ... \geqq f_G$.

If $l = 0$, meaning $f_p \leqq 1/G, \forall 1 \leqq p \leqq G$, one measurement time slot in the measurement cycle is enough to allocate measurement timings for each path p.

On the other hand, $l > 0$ means that for path s where $s > l$, one measurement time slot is enough to allocate its measurement timings. For path t where $t \leqq l$, one measurement time slot is not enough for allocating its measurement timings to satisfy its measurement frequency. In this case, the measurement time slot allocated to path s where $s > l$ is also used to measure path t where $t \leqq l$ when path s is not measured.

In detail, we propose the following scheme for allocating the measurement timings of all paths.

(1) Randomly decide the measurement order of path p ($1 \leqq p \leqq G$) at one measurement circle, and allocate the measurement time slot for each path.

(2) • If $l = 0$,

We measure path p with the probability of Gf_p at the measurement time slot allocated to it.

• If $l \geqq 1$,

– For path t where $t \leqq l$, we measure it at the measurement time slot allocated to it.

– For path s where $s > l$, we measure it with the probability of Gf_s at the measurement time slot allocated to it.

If path s ($s > l$) is not measured, the measurement time slot is used to measure path t ($t \leqq l$) with the probability of $(f_t - 1/G)/\delta$, where $\delta = \sum_{s=l+1}^{G} (1/G - f_s)$.

3.2 Statistical method for improving the accuracy for measurement results

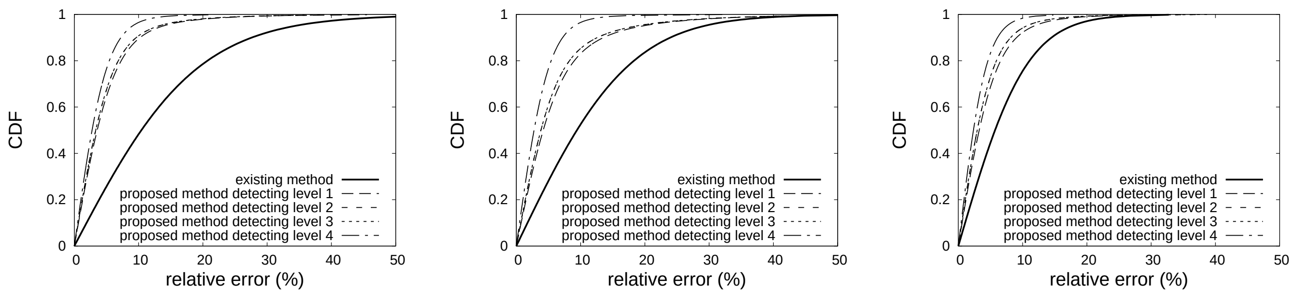
In the proposed measurement methods in Subsect. 3.1, because it is impossible to completely avoid measurement conflicts with partial overlapping paths, the accuracy of the measurement results decreases due to measurement conflicts. Therefore, in our proposed method, overlay nodes exchange measurement results and use statistical processing to improve measurement accuracy. We assume the measuring metric is delay.

We use Fig. 3 to explain the method for path O_iO_j. We assume that the overlapping parts of O_iO_j and its half and partial overlapping paths are divided by routers R_{s_1}, R_{s_2}, ..., R_{s_l}. In the proposed method, the delay measurements are individually conducted for overlapping parts $R_{s_1}R_{s_2}$, $R_{s_2}R_{s_3}$, ..., $R_{s_{l-1}}R_{s_l}$ as well as for end-to-end path O_iO_j. In detail, O_i measures the delays to routers R_{s_1}, R_{s_2}, ..., R_{s_l} and calculates the delay of $O_iR_{s_1}$, $R_{s_1}R_{s_2}$, ..., $R_{s_{l-1}}R_{s_l}$ and $R_{s_l}O_j$ as follows, where the delays of $O_iR_{s_1}$, $O_iR_{s_2}$, ..., $O_iR_{s_l}$, and O_iO_j are denoted as $t_{O_iR_{s_1}}$, $t_{O_iR_{s_2}}$,..., $t_{O_iR_{s_l}}$, $t_{O_iO_j}$, respectively.

$$\begin{aligned} t_{R_{s_k}R_{s_{k+1}}} &= t_{O_iR_{s_{k+1}}} - t_{O_iR_{s_k}} \quad , k = 1, ..., l-1 \\ t_{R_{s_l}O_j} &= t_{O_iO_j} - t_{O_iR_{s_l}} \end{aligned}$$

When part $O_iR_{s_1}$ or $R_{s_k}R_{s_{k+1}}$ is the overlapping part of O_iO_j and its half overlapping path $O_iO_{h_a}$ ($1 \leqq a \leqq G-1$), $t_{O_iR_{s_1}}$ or $t_{R_{s_k}R_{s_{k+1}}}$ is used to calculate the measurement results of both paths O_iO_j and $O_iO_{h_a}$. When part $R_{s_k}R_{s_{k+1}}$ or $R_{s_l}O_j$ is the overlapping part of O_iO_j and its partial overlapping path $O_{u_b}O_{v_b}$ ($1 \leqq b \leqq K_1 - 1$), O_i sends $t_{R_{s_k}R_{s_{k+1}}}$ or $t_{R_{s_l}O_j}$ and its measurement timing to O_{u_b}, so that O_{u_b} can use $t_{R_{s_k}R_{s_{k+1}}}$ or $t_{R_{s_l}O_j}$ to calculate the measurement result of path $O_{u_b}O_{v_b}$.

Finally, we use statistical processing for the data obtained by information exchange to calculate the measurement result of path O_iO_j. First, using the gathered values with the above method, we obtain the average value of the measurement results of $O_iR_{s_1}$, $R_{s_1}R_{s_2}$, ..., $R_{s_{l-1}}R_{s_l}$, and $R_{s_l}O_j$, which are denoted as $\bar{t}_{O_iR_{s_1}}$, $\bar{t}_{R_{s_1}R_{s_2}}$, ..., $\bar{t}_{R_{s_{l-1}}R_{s_l}}$, and $\bar{t}_{R_{s_l}O_j}$, respectively. The measurement result of path O_iO_j is then calculated as follows.



(a) AT&T topology (b) BA topology (c) Random topology

Fig. 4 Relative error of measurement results

Method	number of measurements			number of measurement results			number of concurrent measurements		
	AT&T	BA	Random	AT&T	BA	Random	AT&T	BA	Random
Existing method	10.626	16.034	37.753	10.626	16.034	37.753	1.000	1.000	1.000
Proposed method detecting level 1	7.918	10.531	20.424	130.323	141.577	187.547	1.031	1.030	1.040
Proposed method detecting level 2	8.213	10.593	20.538	136.889	148.918	203.068	1.029	1.027	1.036
Proposed method detecting level 3	8.211	10.602	20.538	136.852	149.077	203.199	1.029	1.027	1.036
Proposed method detecting level 4	6.798	9.286	19.162	168.294	210.704	277.161	1.022	1.018	1.022

Table 1 Average number of measurements, measurement results and concurrent measurements of one link during an aggregation period

$$\bar{t}_{O_iO_j} = \bar{t}_{O_iR_{s_1}} + \sum_{k=1}^{l-1} \bar{t}_{R_{s_k}R_{s_{k+1}}} + \bar{t}_{R_{s_l}O_j} \qquad (2)$$

4. Performance evaluation

In this section, we evaluate the performance of our proposed method by simulation experiments. We explain the evaluation method in Subsect. 4. 1, discuss the simulation settings in Subsect. 4. 2 and present evaluation results and discussions in Subsect. 4. 3.

4. 1 Evaluation method

Here, we assume the measuring metric is delay. We compare the proposed method and the method in [8] with the following metrics:

(1) Measurement accuracy

We use the relative error of the measurement results as a metric to evaluate the measurement accuracy of the methods. The relative error of the measurement result is calculated by:

$$\epsilon = \frac{|\bar{t} - t^*|}{t^*} \qquad (3)$$

where t^* and $\bar{t}$ are the real delay and average values of the measurement results, respectively.

We use the M/M/1 queueing model for each link in the network to calculate t^* and $\bar{t}$. We assume that each measurement on a link causes the increase in the link utilization, that results in the increase of the delay and delay jitter at the link. When the number of concurrent measurements on a link increases, the link utilization also greatly increases, causing additional error in the delay measurements.

(2) System overhead

We consider the following three kinds of overheads in conducting the measurements.

- Path information accessing overhead

This is caused when each overlay node uses `traceroute`-like tools to access the information of the overlay paths.

- Measurement overhead

This is caused when performing measurements on the overlay paths.

- Information exchange overhead

This is caused when overlay nodes exchange information of overlay paths and measurement results with other overlay nodes.

The system overhead, denoted by A, is calculated by:

$$A = \frac{s_a + s_m + s_e}{d} \qquad (4)$$

where d is the duration during which the measurements were performed, and s_a, s_m and s_e are the sizes of the data packets used for accessing the path information, measuring, and exchanging the path information and the measurement results, respectively. We use second as the unit of d and bit as the unit of s_a, s_m and s_e. Therefore, the unit of A is bit per second (bps).

4. 2 Simulation settings

In obtaining the following simulation results, our assumptions on the network topologies, the number and the distribution of overlay nodes are the same as those mentioned in Subsect. 2. 3. 2.

Value β_p, which is used for calculating the measurement frequencies by Eq. (1), is determined based on the coefficient of variance of the measurement results. Furthermore, we adjust the measurement frequencies in our method so that the system overheads of the proposed method and the method in [8] are the same.

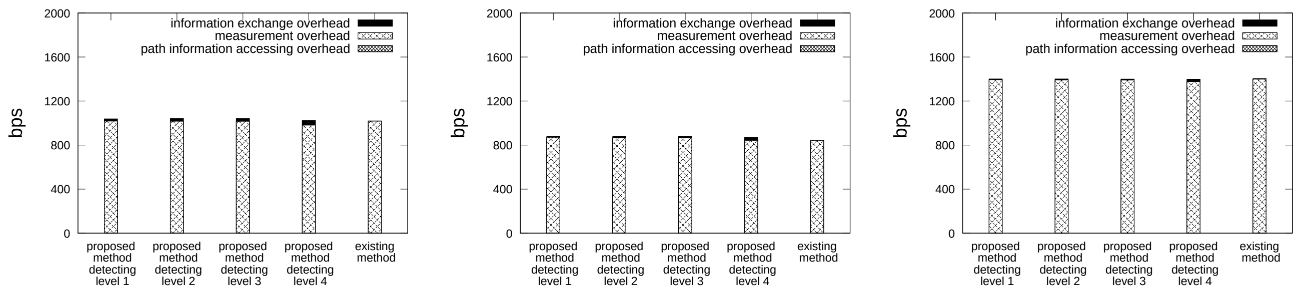
We assume that we utilize `traceroute` to access information of overlay paths, and use `ping` to measure their delays. The size of each `traceroute` packet and `ping` packet is 28 and 475 bytes, respectively. We set the time of each measurement task $\tau = 1$ (second). An aggregation period is set to one hour, and the interval between two times of path information accessing is set to ten hours. We set the utilization of each link in the network to 0.5 and assume that each measurement task increases the link utilization by 0.005.

4. 3 Evaluation results and discussions

4. 3. 1 Measurement accuracy

Figure 4 shows the distribution of the relative error in the measurement results. The relative errors in our method are about half of those in the method in [8]. In our method, the relative errors decrease from detecting levels one to four, and the measurement accuracy of detecting level four greatly surpasses the other detecting levels.

To explain these results, we use the evaluation results of the parameters related to measurement accuracy. Table 1 shows the average number of measurements of an overlay path, the average number of the measurement results of a link (in our method) or a path (in the method in [8]) gathered during an aggregation period, and the average number of concurrent measurements performed at a link. In the method in [8], because measurement results are not exchanged among overlay nodes, the number of aggregated



(a) AT&T topology (b) BA topology (c) Random topology

Fig. 5 Average system overhead of one link

measurement results of an overlay path equals its measurement times. Furthermore, because the measurement conflicts are avoided completely, the average number of concurrent measurements remains one for all links. On the other hand, in our method, as explained in Subsect. 3. 2, the aggregated measurement results of each link of an overlay path include the results obtained from the measurements performed by its source node and the results received from other overlay nodes. Furthermore, because we reduce the measurement conflicts by adjusting the measurement frequencies based on the status of the path overlapping, the average number of concurrent measurements of a link is very close to one.

As shown in this table, in our method, although the number of measuring times is smaller than that in the method in [8], the number of aggregated measurement results is much larger, while the number of measurement conflicts is small. Therefore, the measurement accuracy of our method surpasses the method in [8].

We also observe in this table that when the detecting level of the proposed method is four, the number of measurement results is the largest, whereas the number of concurrent measurements is the smallest. This results in that the measurement accuracy at detecting level four is better than those at other detecting levels.

4. 3. 2 System overhead

Figure 5 shows the average values of the system overhead of the method in [8] and our proposed method with four detecting levels. The system overheads of these methods are almost equal. Furthermore, the measurement overhead occupies the most part of the system overhead, and the information exchange overhead is very small while the path information accessing overhead is negligible. This is because the size of the measurement traffic is much larger than the size of the traffic of information exchange and path information accessing. In our method, the information exchange overhead of detecting level four is slightly larger while the measurement overhead is smaller than those of the other detecting levels. This means that by shifting some amount of overhead from measurement to information exchange, we can significantly improve the measurement accuracy.

We finally conclude that from the results in Figs. 4 and 5, in our method, the detecting level four is the most effective for improving measurement accuracy.

5. Conclusion

In this report, we proposed a distributed overlay network measurement method that reduces the measurement conflicts by detecting the path overlapping and adjusting the measurement frequencies and the measurement timings of overlay paths. We also proposed a method to improve measurement accuracy by exchanging measurement results among neighboring overlay nodes. Simulation results show that the relative error in the measurement results of our method can be decreased by half compared with the existing method when the total overheads of both methods are equal. We also confirmed that exchanging measurement results contributes more to the enhancement of measurement accuracy than performing measurements. In the future, we plan to construct a measurement system that applies the proposed method and investigate its effectiveness in real environments.

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