Interior Link Delay Reference of Ad Hoc Networks Based on End-to-End Measurement: Linear Analysis Model of Delay

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Abstract — **The interior link performance parameter is an important metric to evaluate the Ad Hoc networks, and moreover, to control and optimize the network performance parameters for special applications (i.e., OoS). The object of this paper is to infer the interior link delay in Ad Hoc networks. End-to-End measurement technology is introduced to our research for inferring the link delay probability distribution through End-to-End measurement based on linear analysis model. Simulation results indicate that this method is effective in small scale of Ad Hoc networks.**

***Index Terms*—Ad Hoc networks; End-to-End measurement; link delay inference; linear analysis model of delay**

I. INTRODUCTION

With the increment of network scale and complexity, the requirement for the manageability and measurability for network is becoming higher and stronger than before. The manageability for network is an important metric to evaluate the practicability of networks, since effective manageability is prerequisite to ensuring the network to work well. However, the manageability rests with the measurability of networks, since network traffic, faults, performance and topology varieties could be analyzed accurately and evaluated scientifically through network measurement, which also supports decision making with network material configuration, good performance and maintenance for network systems. Therefore, it is necessary to study network measurement technique.

At present, researchers in the literature have done much work in network measurement area. In general, network measurement technique could be classified as internal measurement and external measurement[1,2]. The frontier is a traditional network measurement technique, which usually adopts a distributed architecture to deploy agents on internal nodes within a network for collecting data, such as loss rate, delay time and traffic etc. and then transfers these data to a central node, on which data are analyzed and computed according to a mathematical model to evaluate the performance of a large network system. Although internal measurement technique has a good measurement precision, it fails to consider the following instances: (1) Network measurement depends on certain network protocol, such as SNMP and ICMP etc., it could not complete network measurement independent of network architecture and protocols. (2) Measurement requires the collaboration among internal nodes, However, by reason of network security and commercial profits, some autonomy areas aren't available for the public, it is difficult to let the internal nodes to collaborate with each other to ensure measurement veracity. (3) Measurement is processed on the assumption that network nodes have ample resources, such as energy and bandwidth etc. However, these assumptions may be more reasonable, since wireless network (i.e., wireless sensor network, Ad Hoc network) measurement had been considered this case.

External measurement as a new network measurement technique is put forward recently, which is also called as NT (Network Tomography)[3-5]. NT adopts Edge-to-Edge or End-to-End path measurement to infer and analyze internal link performance, such as loss rate and delay time, and network logical topology. Network measurement based on NT is consisted of three phases. The first is to build mathematical model, for example, topology model and performance model. The second is not only to measure and collect data from edge of network, but also to evaluate the independence of measurement sample in temporal and spatial factors. The last is to analyze measurement sample, where statistical theory could be used to analyze and evaluate the measurement samples, and then to infer the internal link performance. Thus it can be seen above that NT measurement technique is different from internal measurement.

Mobile Ad Hoc network (MANETs) is a collection of wireless mobile nodes composed of a self-configuration, self-organization, multi-hop wireless network with dynamic characteristic of network topology without using any existing infrastructure, which has a promising future in military and civil application domains. With the increment of Ad Hoc network application, higher requirements of performance need to be obtained through network measurement, which is important for Ad Hoc theory research, practical deployment and performance evaluation. Through network measurement, working state of Ad Hoc network and dynamic characteristic could be analyzed and evaluated not only to adjust, re-deploy and resume the disabled network, but also to find the bottleneck node and to obtain network performance view, so that network resources could be optimized and redeployed.

However, recent research about Ad Hoc network mainly focus on the system architecture, network router protocol, self-organization and self-management, little on network performance measurement. The main reasons are as the following: (1) Ad Hoc network as a new one, its architecture and communication protocols have not been standard by international standard organization concerned. Traditional network measurement technique could not be used in Ad Hoc network for the dependence with certain network protocol. (2) For the self-organization characteristic, Ad Hoc network work in the mode of self-configuration and self-management during different phases (i.e., deployment, work and death). Traditional measurement technique does not adapt to this characteristic for requiring the collaboration and communication between internal nodes. (3) Traditional measurement technique builds on the basis of having infrastructure, steady network topology and wired network, which does not adapt to Ad Hoc network for having no-infrastructure and the effect of dynamic characteristic on measurement. Therefore, in allusion to the characteristic of Ad Hoc network, a new measurement must be founded to meet the requirement of network measurement.

In the process of measuring the performance of Ad Hoc network based on End-to-End measurement technology, the dynamic characteristic of link topology directly influences the measurement results[6~7]. If the measurement could be completed under the condition that link topology remains relatively invariable, which maybe improve the veracity and precision of performance measurement[8~10]. In our pervious works, the positions of mobile nodes in Ad Hoc networks at any moment could be obtained through link topology snapshots capturing algorithms according to analyzing on the scenario files of mobility models, and then the serials of snapshots of physical topology could be archived. The different periods during which physical topology is invariable can be gained by analyzing on the snapshots statistically, which is called as measurement window time in this paper. According to the results of analysis on the scenario files of RW, RWP, RGMP, and Manhattan mobility models[10~12] , we could safely arrive at the conclusion: measurement window time will appear periodically in the whole simulation time.

During measurement window time, since the state of link in Ad Hoc network could not vary, the inference results of link performance based on the samples of End-to-End measurement could reflect the interior link characteristics effectively. We call this phenomenon as time validity in the measurement of Ad Hoc network. This paper presents a interior link delay reference algorithm of Ad Hoc network on the basis of End-to-End measurement method. The main content of this algorithm is as followings: First to obtain the measurement time window through a link topology snapshot algorithm, Second to build up a measurement model and linear delay analysis model for Ad Hoc networks, Third to complete End-to-End measurement, Forth to refer interior link delay of Ad Hoc network according to measurement data sample, correlation among mobile nodes in Ad Hoc network topology, linear delay analysis model and mathematical statistics theory.

In short, research on Ad Hoc network measurement theory model and method is a key problem to develop Ad Hoc network technology. NT adopting End-to-End measurement as a new theory and method independent of the collaboration among intra-nodes is feasible verified by former research works. Therefore, research on the Ad Hoc network measurement theory and method based on NT technique could not only improve the manageability and measurability of Ad Hoc network, but also provides the application of measurement in Ad Hoc network with basic theory basis.

II. RELATED WORKS

Recently much research on NT technique has been studied. [13][14] have studied the NT theory and key technique systematically, the achievement of which establish the theory of NT measurement technique, especially the MINC(Multicast-based Inference of Network-internal Characteristics) project in AT&T and University of Massachusetts Boston[15] , and Unicast NT Project in Rice University[16]. Caceres first brings forth to adopts multicast and introduces the concept of packets correlation to infer the loss rate on the assumption that network logical topology has known. Subsequently N. G. Duffield and L. Presti et. put forward to inferring link delay time distribution based on multicast. Coates and Nowak in Rice University use unicast packet pairs in NT measurement. However, all research on NT measurement technique above mainly focus on wired network, especially internet, not related to wireless network.

With the development of network measurement, NT has be used in wireless network measurement field now(i.e., 3G network, wireless sensor network). H X Nguyen[17] et. use Maximum Likelihood Estimation method and Bayesian theory to infer and find the link with higher loss rate through End-to-End measurement in wireless network. [18] uses NT technique in 3G network to infer link performance, for example, it infers and evaluates the RAN (Radio Access Network) performance through collecting the data from core network(CN) . However, all the research above fails to consider the factor of dynamic characteristic of network topology, it does not adapt to Ad Hoc network link performance measurement.

At present, Ad Hoc network performance measurement mainly focus on traditional network intra-measurement technique. [19][20] bring forth to use active probing in Ad Hoc network to measure available bandwidth. [21] puts forward a DEAN (Delay Estimation in Ad Hoc Networks) protocol, in which neighbor nodes uses Hello message to exchange delay time between each other, that is, to measuring delay time needs the collaboration of intra-nodes. All the research above actually is traditional intra-measurement, which has many faults as described above.

Above all, there are many theory problems to be solved in Ad Hoc network measurement. At fist, how to deal with the influence of dynamic characteristic of network topology on performance measurement is a key issue. Second, measurement model and inference method is another key issue to be dealt with in NT measurement of Ad Hoc network.

The contribution of this paper lies in the following points: (1) Introducing the End-to-End measurement technology to inferring the link characteristic of Ad Hoc networks (i.e., link delay probability distribution) based on the samples of End-to-End measurement; (2) Analysis on the linear model to infer the link delay in Ad Hoc networks.

The rest of the paper is organized as the followings: Section 3 proposes the system model comprising measurement model and interior link delay analysis model. The algorithm of link delay inference based on linear analysis model is presented in section 4. Simulation and result analysis are discussed in section 5. Finally, we describe the concluding remarks and future work in section 6.

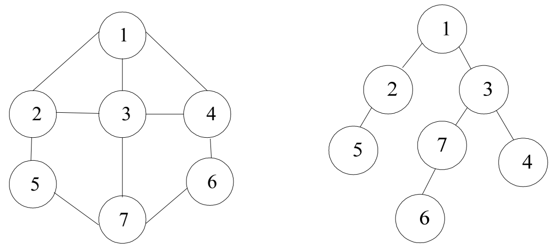
III. SYSTEM MODEL

System model is the foundation on the interior link performance inference of Ad Hoc networks based on End-to-End measurement, which is composed of measurement model and interior link performance analysis model. Since the paper aims to do some research on link delay inference of Ad Hoc networks, performance analysis models mainly refer to interior link delay analysis model in this section.

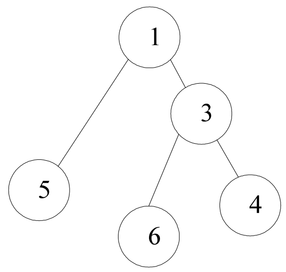
A. *Measurement Model*

In view of different points, Ad Hoc network topology could be classified as Physical topology (often called as link topology), network routing topology and logical network topology. Physical topology represents the direct connectivity among routers and switches in Internet, nevertheless, since mobile nodes in MANET play the roles of sender, receiver, especially of transmitter to forward packets, they use wireless medium to connect each other. Therefore, when mobile nodes comes within the transmission range of each other and packets from each other could be successfully decoded, we call there is a physical connectivity between the two nodes. Many different physical connects constitute the physical topology, which actually is a no-direction graph. Network routing topology is founded on the basis of physical topology with the routing information, which represents the paths that packets traverse over from senders to receivers.

If there are seven mobility nodes, whose physical topology is a no-direction graph as Fig. 1(a) at time t , and we denote node 1 as sender, node 4, 5, 6 as receivers, then the network routing topology actually is a tree architecture as in Fig.1(b). Network routing topology often is used for performance analysis on a new routing protocol. Logical topology is based on network routing topology used for NT (Network Tomography) measurement of network, especially, used for Ad Hoc network topology inference, which only studies on the branching nodes and joint nodes. In logical topology architecture, all nodes except source sender and receivers have at least two input degrees or two output degrees as in Fig.1(c), where the performance of link between node 1 and 5 covers that of node 2, and performance of link between node 3 and 6 covers that of node 7.



(a) Physical topology (b) Network routing topology



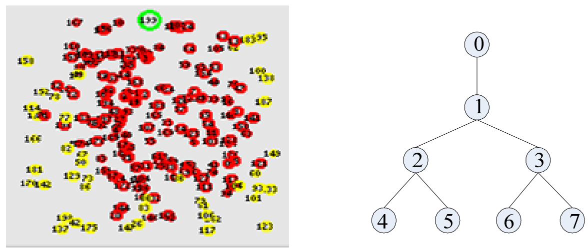
(c) Logical topology

Fig. 1 Ad Hoc network topology architecture

In this paper, we introduce physical topology snapshot capturing method to deal with the influence of dynamic characteristic of network topology on measurement, because this method could be used to obtain the lifetime slices of Ad Hoc network, during which physical topology does not varies any more. If not considering the factor of load balance in routing protocol, we can safely reach the conclusion that routing topology and physical topology will keep invariable during lifetime slice. If NT measurement on Ad Hoc network could be completed during each lifetime slice, the influence of dynamic characteristic of network topology will be avoid. We suppose that during a certain lifetime slice, the logical topology of Ad Hoc network is as in Fig. 2.

Firstly, the measurement window time and its static physical topology architecture could be obtained through the algorithm of link topology snapshots as in Fig.2(a), then the users could choose the interested nodes (i.e., from node 0 to node 7) according to the application requirement to constitute a measurement model as a tree-type in Fig.2(b).

In Fig.2 (b), Let $T=(V, L)$ denote a reverse tree with the node set V and link set L. V could be finely classified as $V=\{S,M,R\}$, where S denotes the set of sender nodes, M the set of inter-media nodes and R the set of leaf nodes(or receiver nodes).The link set contains ordered pairs (i, j) such that node i sends its data to node j directly, destined for the leaf node $r(r\in R)$. The link (i, j) is simply denoted by link i. The path from the node i to j is denoted by $path(i\rightarrow j)$, Let f(i) denote the father set of the node i. The ancestor set of node i could be denoted as $F(i)=\{f^1(i),f^2(i),...,f^n(i)|f^n(i)\in S\}$, note that there exists the following rules: $f^0(i)=i$, $f^1(i)=f(i)$ and $f^n(i)=f(f^{n-1}(i))(n\geq 1)$. Because the logical topology will remain static during measurement window time, which satisfies the precondition of End-to-End measurement technology applied for Ad Hoc networks.



(a) snapshot of physical topology (b) measurement model

Fig.2 Ad Hoc measurement model

B. Link Delay Linear Analysis Model

On the assumption that we have done the measurement experiments m rounds. Each round we could get the End-to-End delay vector of receiver i denoted as $Y_i=\{y_{i,1},y_{i,2},...,y_{i,m}\}$ ($1\leq i\leq n$), where n is the number of leaf node, and $y_{i,j}(1\leq j\leq m)$ is the sample of stochastic variable $Y_i(i\in[1,n],Y_i\in[0,\infty])$. After the m times experiments have finished, the delay probability distribution of the End-to-End measurement could be obtained as: $P(Y)=\{P(Y_1),P(Y_2),...,P(Y_n)\}$. If the estimated link delay probability distribution is denoted as $P(X)=\{P(X_1),P(X_2),...,P(X_v)\}$, then the maximum likelihood function could be expressed as formula (1):

$$L(Y;X)=P(Y_1,Y_2,...,Y_n;X_1,X_2,...,X_v)=\prod_{i=1}^{n}P(Y_i;X) \quad (1)$$

When Formula (1) equals to the maximum, we use $X' = \arg_X \max \prod_{i=1}^{n} p(Y_i;X)$, where $X' = (X_1', X_2', ..., X_n')$, as the estimated value of link delay *X*. However, the maximum likelihood estimation algorithm[22~24] is very difficult to obtain the estimated value of link delay *X* for computing complexity. In order to obtain the link delay X, [25] adopts the expectation maximum (EM) algorithm including two procedures: E-step and M-step. The main problem about EM algorithm is that it could obtain the partially optimized solution, not the unitary optimized one. For the sake of computing complexity increasing by the scale of network, Pseudo-EM Algorithm[26]decomposes a large scale problem to several small scale ones. The maximum likelihood of these small scale problems could be expressed as:

$$L\ (Y_1, Y_2, ..., Y_n; X) = \prod_{i=1}^{n} \prod_{s \in S} P^s(Y_i^s; X^s) \qquad (2)$$

where S is set of all small scale problems. The method to get the solution for Formula (2) is similar to that for Formula (1). The Bayesian estimation method[27, 28] uses the former probability distribution of link delay to infer the posterior one, however, how to get the former probability distribution is a difficult work.

The linear analysis model of delay will be presented next. As we all know, the delay of $path(i \to j)$, denoted as $d(i, j)$, is the sum of all link delay along this path, denoted as $d(k)$ ($k \in F(j) \cup \{j\}$), that is,

$$d(i, j) = \sum d(k)(k \in F(j) \cup \{j\}) \qquad (3)$$

In the End-to-End measurement of Ad Hoc networks, the node i belongs to the set of S, and node j to the set of R. The task of link delay inference is to infer $d(k)$ according to the measurement samples of $d(i, j)$. If we only utilize one formula, it is impossible to infer $d(k)$. In order to obtain the link delay, we must use multi-formula and constitute simultaneous equations to resolve the link delay. The simultaneous equations could be expressed as formula (4).

$$Y = AX + \varepsilon \qquad (4)$$

Formula (4) is referred to as interior link delay linear analysis model of Ad Hoc network in this paper. In Formula (4), *Y* is the delay of path which could be obtained or observed in End-to-End measurement procedure. cis the traffic matrix, and ε is the noisy which is ignored in this paper. *X* is the interior link delay of Ad Hoc network. Our task is that on the condition of Y and A known, ε ignored, how to resolve X. The solution of *X* is concerned with the types of A. In the next section, we will present the algorithm of link delay inference on the condition of A being square traffic matrix and non-square traffic matrix. The traffic matrix A of Ad Hoc networks logical topology could be expressed as in Fig. 3.

$$Matrix(A) = \begin{matrix} & Link1 & Link2 & Link3 & Link4 & Link5 & Link6 & Link7 \\ path(0 \to 4) & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ path(0 \to 5) & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ path(0 \to 6) & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ path(0 \to 7) & 1 & 0 & 1 & 0 & 0 & 0 & 1 \end{matrix}$$

Fig. 3 Traffic matrix A

IV. ALGORITHM OF LINK DELAY INFERENCE

To compute the formula (4) is equivalent to resolve a non-homogeneous linear equations according to linear algebra theory. According to different type of traffic matrix A, we will divide two types(i.e., square traffic matrix and non-square traffic matrix) to discuss how to resolve the solution space for the formula (4) in this section.

A. Square Traffic Matrix

When the traffic matrix is a square one, the solution for the non-homogeneous linear equations as formula (4) is concerned with the rank of the traffic matrix A. If the rank of traffic matrix A is full, there is a unique solution for the non-homogeneous linear equations, otherwise, the question of solution for the equation in section 3.1 is translated to that of a non-square traffic matrix problem. Now we only consider the A as a full rank traffic matrix. At first we could obtain the reverse matrix of A denoted as A^{-1}, the interior link delay can be expressed as formula (5).

$$X = A^{-1} \times Y \qquad (5)$$

If the sender node sends N probes to every leaf nodes in Fig. 2(b) respectively, then every link delay in Ad Hoc networks could be achieved according to Formula (5) at different N time. However, we do not care about the link delay at different time, but are concerned about the link delay probability distribution during measurement window time, which could be obtained through analyzing on the link delay statistically during measurement window time based on the discrete link delay time.

In practice, it is not possible to construct a square traffic matrix A in Ad Hoc networks. There is only one case that if there are N mobile nodes in Ad Hoc network, only one node is the sender, the other *N-1* nodes are all leaf nodes. Under this condition, it is not necessary to use End-to-End measurement technology to infer the link delay, since there is only one step between the sender and leaf nodes, we could obtain the link delay directly through measurement.

B. Non-square Traffic Matrix

When the rank of traffic matrix A is not full, or the traffic matrix A is a non-square matrix, the problem in section A is translated to how to resolve a non-homogenous linear equations. We will discuss this problem from the following two sides.

(1) When the rank of the traffic matrix A is not equal to that of its augmentation matrix(i.e., $A \mid Y$), there is no solution for the non-homogenous linear equations.

(2) When the rank of the traffic matrix A is equal to that of its augmentation matrix, there is a solution space for the non-homogenous linear equations. If the traffic matrix A is denoted as $A=(a_{i,j})_{m\times n}$, and rank(A)=rank($A \mid Y$)=r($r < n$), then the solution space is composed of n-r characteristic solutions (i.e., $\{\eta_i\}(1 \le i \le n-r)$) for the homogenous linear equations and one special solution(i.e., β) for the non-homogenous linear equations. Therefore, the solution space of the non-homogeneous linear equations could be denoted as the following formula (6).

$$S=\sum_{i=1}^{n-r} k_i \times \eta_i + \beta \tag{6}$$

Since the solution space S comprised of infinite solutions, it is necessary to limit the scale of solution space. The link l ($l \in L$) delay inference result is as Formula (6), which is shared by χ paths. If the End-to-End delay of the χ paths is denoted as $\mathrm{T}_j(1 \le j \le \chi)$, the minimum delay of the χ paths Γ could be expressed as the following formula (7).

$$\Gamma = \min\{\mathrm{T}_j(1 \le j \le \chi)\} \tag{7}$$

Then the solution space S could be reduced to Ω :

$\Omega=\sum k_j \times \eta_j + \beta(\Omega \subset S, 0 \le k_j \times \eta_j + \beta \le \Gamma)$.

Next it is similar to the section ***A*** that we could obtain any link delay probability distribution through analyzing on the N times of solution space based on the discrete delay time. The unique difference between the square traffic matrix and non-square traffic matrix is that the lessen solution space maybe belongs to many discrete bins, but unique solution only to one bin.

The algorithm of interior link delay probability distribution is as the following **Algorithm 1.**

Algorithm 1 Link delay probability distribution algorithm

Step1: To discrete the link delay time.

Step2: $Count = 0$, and to compute the rank of traffic matrix A and augmentation matrix $A \mid Y$. If $rank(A) \neq rank(A|Y)$ is true, **Goto step10.**

Step3: To compute the characteristic solution for the homogenous linear equations as $\{\eta_i\}(1 \le i \le n-r)$

Step4: To compute the special solution for the non-homogenous linear equations as β

Step5: To construct the solution space for the non-Homogenous linear equations as

$$S = \sum_{i=1}^{n-r} k_i \times \eta_i + \beta$$

Step6: To reduce the scale of S to Ω **.**

Step7: $Count++$.

Step8: If $Count < N$ (N is the times of End-to-End measurement), **Go to Step3**.

Step9: To compute the link delay probability distribution through analyzing on the link delay in all N times statistically based on discrete delay time.

Step10: Finish.

C. Delay time discrete method

Let Θ be a set of finite delay, and link delay time $\theta_j(1 \le j \le 15)$ is discretized to Θ, then θ_j takes a value in Θ . If we suppose that discrete parameter is α , then bin size of delay time is $1/\alpha$, and the set Θ could be defined as following formula (8) based on the fixed bin size delay time discrete model.

$$\Theta = \{0, 1/\alpha, 2/\alpha, \dots i/\alpha \dots, 1\}(i \in [0, \alpha]) \tag{8}$$

Then discrete function of delay time could be defined as the following formula (9)

$$\underset{(i \in [0,\alpha],\, j \in [1,\infty])}{Discrete-Function(\theta_j)} = \begin{cases} 0 & \theta_j \in [0, 1/2\alpha] \\ i/\alpha & \theta_j \in (\frac{i}{\alpha}-\frac{1}{2\alpha}, \frac{i}{\alpha}+\frac{1}{2\alpha}] \\ 1 & \theta_j \in (\frac{2\alpha-1}{2\alpha}, 1] \end{cases} \tag{9}$$

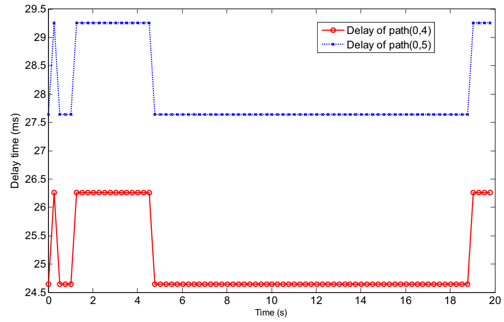
The value of α is an important factor to influence the reference accuracy and computing complexity. If α is small, although more discrete delay time zone and reference accuracy could be obtained, the computing complexity will increase quickly. Otherwise, in despite of computing complexity being reduced, discrete delay time zone and reference accuracy will be reduced. Therefore, it is necessary to make a compromise between computing complexity and reference accuracy according to difference application requirement.

V. SIMULATION AND RESLUT ANALYSIS

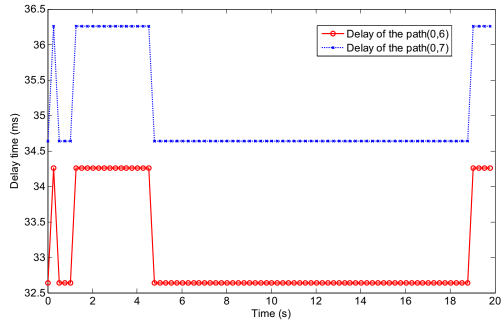
In this section, at first we use the NS-2 tool to simulate the mobile scenario of Ad Hoc network and implement the End-to-End measurement to verify algorithm 1. Finally we give the results analysis of simulation.

A. Simulation

In order to verify the algorithm 1 of link delay probability distribution in section □(A), a scenario of Ad Hoc networks based on NS-2[29] is built up. There are 20 mobile nodes in $1200m \times 1200m$ square area. We use RW mobility model with the maximum velocity being 10m/s and simulation time being 900s. we applied the algorithm of link topology snapshots for capturing the snapshots of physical topology through analyzing on the scenario file of RW mobility model. The results indicate that there is one measurement window time from 816.5s to 837.5s, that is, the measurement window time is 21.0s. During the measurement window time, because physical topology remain static, we random choose node 0 to node 7 as our interested nodes which construct a tree-type logical topology as in Fig 2(b). Node 0 is the sender node, and node 4,5,6,7 are the leaf nodes(or receiver nodes). Considering of the temporal relativity, we use UDP multicast packets as the probes, the size of which is 40Bytes and the velocity of which is 4Packets/s. The background flows also adopt UDP multicast packets, the size of which is 128Bytes and the velocity of which is 40Packets/s. The delays of link 1, 2, 3,4, 6, and 7 are set as 4ms, 8ms, 10ms, 12ms, 15ms, 18ms, and 20ms respectively. Through simulation, the delays of different path (i.e., path(0,4), path(0,5), path(0,5), path(0,6)) could be obtained and are shown as Fig.4.



(a) The delay of the path(0,6) and path(0,7)



(b) The delay of the path(0,6) and path(0,7)

Fig. 4 The delay of path

Next, we use algorithm 1 to infer the delay probability distribution of different links in Fig.2 (b) according to the theory of non-homogeneous linear equations. The solution space is as formula (10).

$$s = k1\begin{bmatrix}-1\\1\\1\\0\\0\\0\\0\end{bmatrix} + k2\begin{bmatrix}0\\-1\\0\\1\\1\\0\\0\end{bmatrix} + k3\begin{bmatrix}-1\\1\\0\\0\\0\\1\\1\end{bmatrix} + \beta \qquad \text{Formula (10).}$$

In order to simplify the complexity of computing the solutions for the non-homogenous linear equations, we only computed the optimization solutions statistically as TABLE 1.

TABLE 1. INFERENCE RESULTS

Link	1	2	3	4	5	6	7
Delay(ms)	4.64	8	10	12	15	18	20
Probability	76.4%	100%	100%	100%	100%	100%	100%

As seen from TABLE 1, all the other interior link delay optimization solutions except link 1 are refereed correctly by using the method in this paper. In next section we will explain the theory base of linear analysis model.

B. Results Analysis

Simulation results showed that the algorithm of interior link delay probability distribution was effective. The basic theory of the method in this paper is that multicast probes experience a common delay on the shared links. Next, correlative degree is introduced to evaluate the intensity of this characteristic as the following CS:

$$CS = \sum \mu_i / n$$

Where μ_i denotes the number that link i belonged to different paths, and $n = |L|$ the sum of different link in logical topology. Next we use the binary tree as an example to analyze the parameter CS.

Theorem 1: The CS of a binary three is only related to its depth .

Proof:

If the depth of a binary tree is k , at the 1-th layer, there is only one node and it belongs to the 2^{k-1} different paths. At the 2-th layer, there are two nodes, erveryone of which belongs to the $2^{k-1}/2$ different paths. In the same way, at the i-th layer, there are 2^{i-1} nodes and each node belongs to $2^{k-1}/2^{i-1}$ different paths. Then, $\sum \mu_i$ could be denoted as the following.

$$\sum \mu_i = 2^0 \times 2^{k-1}/2^0 + 2^1 \times 2^{k-1}/2^1 + \ldots + 2^{k-1} \times 2^{k-1}/2^{2k-1}$$
$$= \sum_{i=0}^{k-1} 2^i \times 2^{k-1}/2^i$$
$$= k \times 2^{k-1}$$

However, there are $2^k - 2$ different links in a binary tree, according to the definition of CS, we could get the following formula:

$$CS = k \times 2^{k-1} / (2^k - 2)$$
$$\approx k/2$$
$$= o(k)$$

Therefore, the theorem 1 is proved.

Deduction 1. the CS of a tri-tree is only related to its depth (i.e., k), and $CS = O(k)$.

Finally, we analyze on the spatial complexity of algorithm 1. Storage space is mainly used for traffic matrix A . In a full binary tree with the depth being k, the scale of traffic matrix A is $(2^k - 2) \times 2^{k-1}$, therefore, spatial complexity could be denoted as $SP = O(2^k)$. Thus it can be seen that the storage space is increased with the depth of binary-tree exponentially. Therefore, the algorithm 1 is only adaptable to the small scale of Ad Hoc networks.

VI. CONCLUSION AND FUTURE WORK

The paper resolved the problem of interior link delay inference through computing the solution space for the non-homogenous linear equations based on linear analysis model of delay. Although this method is effective in small scale of Ad Hoc networks, it is necessary to study and find another inference method adaptable for the large scale of Ad Hoc networks in our future works. We will introduce Pseudo-EM Algorithm[26] to decompose a large scale problem to several small scale ones for the sake of computing complexity increasing by the scale of network in our future work. The method in this paper validates that it is feasible to infer interior link delay of Ad Hoc network based on End-to-End measurement in theory. How to introduce the method in this paper to practical Ad Hoc network measurement engineering is another future work. Firstly, we must find the statistical characteristic of link topology steady period (i.e., window time of measurement) by using stochastic processes theory. Secondly, we will apply NT technology to infer the Ad Hoc network logical topology, interior link delay time and loss rate, which is very important to evaluate Ad Hoc network performance, to find out the fault nodes or links and to control QoS parameters.

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