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Towards an AS Level Network Performance Model

Huan Xiong, and Ming Chen

Abstract**—**In order to research Internet quantificationally and better model the performance of network, this paper proposes a novel AS level network performance model (MNPM), it takes autonomous system (AS) as basic modeling unit, measures E2E performance between any two outdegrees of an AS and organizes measurement results into matrix form which called performance matrix (PM). Inter-AS performance calculation is defined according to performance information stored in PM. Simulation has been implemented to verify the correctness of MNPM and a practical application of MNPM (network congestion detection) is given.

Keywords**—**AS, network performance, model, metric, congestion.

I. Introduction

IT has been a long time since the research community wants to analyze the performance of Internet quantificationally [1,2]. Only in this way the behaviors and characteristics of Internet in whole or in part can be understood, the Internet performance model be established, and the research on Internet be built on scientific foundation.

We can not duplicate and analyze Internet as a whole system in laboratory environments. Only with reasonable model and simulation, can Internet be researched scientifically. Internet is a complex system, its architecture is layered, and intricate interactions exist between protocols and entities in different layers. Different network applications have their own unique behaviors, and network traffic manifests distinct characteristics under different temporal scales and spatial scales. Generally speaking, current network performance modeling and analysis is implemented within certain context and have their own limited scopes to investigate network performance and operating states, with those models, network performance is analyzed in certain extent. In node level, queuing disciplines, buffer size, scheduling and policing mechanism of routers and switches are analyzed to determine their QoS performance [3]. In end-to-end performance of network level, mechanisms of TCP (like congestion control, RTT, bandwidth, and fairness, etc.) are modeled and analyzed to understand this most extensively used protocol [4,5]. In IP path level, router level and AS level, network topology is needed to model and analyze respectively to discovery and understand properties of the complex network [6]. It is easy to understand that almost all current Internet modeling methods are one-dimensional and their research objectives are limited to certain points or partial path in certain level of network. Dealing with increasing complex networks, those models and corresponding analysis methods are not suitable for analyzing the performance of network as a whole. For example, when designing a new network or evaluating an existing network, a simple and effective method is absent to evaluate and rank the performance of the network as a whole, so that we have no quantificational way to tell which candidate AS is better that many other ASes. In fact, it is difficult to evaluate the performance of network as a whole with metrics like E2E TCP performance or AS shortest path length only. We need eagerly a novel network performance model which can describe the performance of network as a whole.

So the Matrix based Network Performance Model (MNPM) is proposed in this paper. This model aims to describe the performance of network as a whole. With MNPM, AS is regarded as basic performance describable unit and is abstracted into a performance node, then the whole Internet may be abstracted into an overlay network composed of connected performance nodes. Although each AS is administrated by one ISP and adopts the same policy within it, the internal structure of AS is always very complex, variety of communication technologies, routing protocols and resource allocation schemes are used. All those make it harder to model and analyze network in a unified way. We manage to hide the complexity however. If we deal with this problem in point of view of the performance of target AS that expose to the outer world, the performance of the AS may be modeled in matrix form, elements of the matrix stand for E2E performance between any two outdegrees of the AS.

In Section 2 related works are mentioned. In Section 3 AS performance model is investigated and then MNPM is proposed. In Section 4, the algorithm of calculating MNPM based inter-domain performance is described. In Section 5, the feasibility and correctness of MNPM is verified by simulation. By getting the value of RTT matrix determinant, an instance applying MNPM to judge whether congestion exists in an AS is illustrated in Section 6. Section 7 summarizes our paper work.

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Huan Xiong is with the Department of Computer, PLA University of Science and Technology, Nanjing 210007, China (phone: 86-25-80824588-816; e-mail: raccoonhuan@yahoo.com.cn).

Ming Chen is with the Department of Computer, PLA University of Science and Technology, Nanjing, China 210007 (phone: 86-25-80824588-801; e-mail: mingchen@public1.ptt.js.cn).

II. Related Works

We classify related works into three categories: network measurement technology and tool, measurement infrastructure, network model and analysis method.

Measurement technologies and tools measure and monitor the quantitative activity of network, reveal characteristics of network in different aspects. The measured metrics that related with our works including different kinds of E2E metrics (e.g. RTT, packet loss, and bandwidth) and network topology (we only interested in AS level topology). Representative measurement tools including ping for RTT, bProbe [7] for bandwidth, ZING for packet loss [8], and pathchar [9] for characteristics of link. AS level topology measurement analyzes raw data including BGP RIB and update [10], skitter [11], and registry information (like WHOIS [12]) to construct AS level topology. Those technologies and tools provide first-hand information about running states of Internet, based on which performance model and analysis of Internet can be built.

Measurement infrastructures are deployed network wide with certain synchronization mechanism, they usually employ different measurement tools synthetically to capture the activities of Internet in a whole and distributed manner. For example Surveyor [13] uses ping-like probes to measure RTT and packet loss, skitter uses dozens of monitors strategically placed in the global Internet and sends traceroute probes to measure RTT and route level topology. NIMI [14] enables general Internet measurements to be managed securely across a diverse set of hosts.

Network models are built upon measurement to describe and simulate activities of network, they are used in network performance prediction, network control and resource allocation. Because of the complexity, heterogeneity and variance of Internet, the work is extremely difficult to carry out and not yet well developed. Existing works include graph model, Petri nets, formal grammars and fluid model, etc. Analysis methods are used to exact information from measurement data, examples are wavelet, fractal [15], and statistical means, etc.

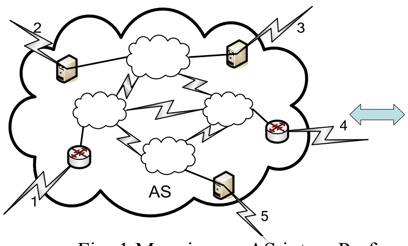
III. Matrix based Network Performance Model (MNPM)

Because of the complex internal structure of AS, it is difficult to represent the performance of an AS according to its traffic pattern or internal structure. However if observed from outside, imagine measuring the E2E metric (like RTT and bandwidth) between any two inter-domain traffic outlets of an AS (the concept of AS outlet is defined below), and organize the result into a matrix, E2E performance the AS exposes to outside world could be know without knowledge of the internal details of the AS. This method is called Matrix based Network Performance Model (MNPM). First we define relative concepts and then give the definition of network model used in this paper.

Definition 1 AS and Inter-domain Outlet (IDO): An AS is a collection of network devices and hosts under the same administration and routing policy. If an AS can be left away from by at most one hop through some interface of a border route of the AS, the interface is defined as Inter-domain Outlet (IDO). ASes interconnect with each other through IDO. Each AS has at least one border router, and each border router has at least one IDO. IDO interconnect with each other through Inter-domain Connection (IDC).

Definition 2 Inter-domain Connection (IDC): If it is reachable from an IDO of an AS to an IDO of another AS without passing through any third AS, the inter-domain link traversed is defined as Inter-domain Connection (IDC). Performance of IDC is modeled as $n = \{p, q\}$, p and q respectively represents the bidirectional E2E performance of the IDC.

Definition 3 Performance Matrix (PM): Assume an AS has K IDOs, performance of the AS is stable within certain period of time. At time t the E2E performance from IDO i (i=1, 2, … $K-1$) to other $K-1$ IDOs is measured, the $K\times(K-1)$ results are placed into a $K \times K$ matrix $m_{K\times K}$ which is called Performance Matrix (PM). Element $m[i][j]$ ($1\leq i,j\leq K$) of PM $m_{K\times K}$ represents the E2E performance from IDO i to IDO j, and because of network asymmetry, usually $m[i][j]\neq m[j][i]$. According to the definition of PM, element $m[i][i]$ ($1\leq i\leq K$) is non-physical, because the route from IDO i to IDO i is a loop, it is illegal and shouldn't exist. Fig. 1 shows an AS with 5 IDOs, the performance of this AS is represented as an $m_{5\times 5}$ PM.



$$M = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{15} \\ a_{21} & a_{22} & \cdots & a_{25} \\ \cdots & \cdots & \cdots & \cdots \\ a_{51} & a_{52} & \cdots & a_{55} \end{bmatrix}$$

Fig. 1 Mapping an AS into a Performance Matrix

Based on above definitions, network model used in this paper is defined as following:

Definition 4 Network: Network G is defined as $G=\{V, E, M, N\}$, where V is collection of AS, E is collection of IDC, M is collection of PM and N is collection of performance of IDC. Detailed description of V and E is as following:

For any $v\in V$, $v = \{O, m\}$, where O is collection of IDO of this AS; $m\in M$, is the PM of this AS.

For any $e\in E$, $e = \{o_i, o_j, n\}$, where o_i, o_j are two IDOs that are connected by IDC e, and belong to two different ASes. $n\in N$, is the performance of IDC e.

Two properties of the network model are:

Property 1: At most one IDC between any two ASes.

Property 2: The dimension of a PM is equal to the number of IDO of that AS, and equal to the number of IDC that connect that AS.

There are several advantages to describe the performance of AS level network with MNPM: 1. Information hiding. MNPM only cares about the E2E performance between two IDOs of an AS, rather than the detailed structure inside the AS. In this way the complexity and heterogeneity is hidden behind like in a black box. 2. Easy deployment. The probes used to measure PM of an AS are required to deploy at IDOs of that AS, thus without the necessity of considering where to deploy probes like most measurement infrastructures have to do. 3. Easy administration. Since probes used to measure PM of an AS are all deployed within the same AS, thus under the same administration. AS administrator has full control over the measurement infrastructure. 4. Security guarantee. PM only reveals E2E performance of an AS, it doesn't leak any crucial information of that AS such as interior routing policy and business relationship.

IV. MNPM for Multi-AS

Router level E2E path of Internet can be described as a directional sequence $<h_0, l_1, h_1, \ldots, l_n, h_n>$, where $n > 0$, h_i is node, l_i is link from h_{i-1} to h_i. In the middle of each $h_1 \ldots h_{n-1}$ is a router. Similarly, AS level E2E path can be described as a directional AS sequence like $<AS_1, AS_2, \ldots, AS_N>$, assume these ASes are physically connected, and the AS path is permitted by policy. Therefore MNPM should have the ability to describe the E2E performance across this AS sequence. The basic idea to address this problem is based on the AS PM proposed in Section 2, implementing certain kind of computation on PMs of ASes along the directional AS sequence, and finally figure out an Inter-AS Performance Matrix (Inter-AS PM).

Definition 5 Inter-AS Performance Matrix (Inter-AS PM): For a directional AS sequence $<AS_1, AS_2, \ldots, AS_N>$, assume the corresponding PMs are $M_1, M_2, M_3, \ldots, M_N$, then the E2E performance from AS_1 to AS_N along the AS sequence can be described as $M = o\ (M_1, M_2, M_3, \ldots, M_N)$, where M is Inter-AS PM, o is PM aggregate function. If AS_1 has m IDOs and AS_N has n IDOs, M is an $m \times n$ matrix. The element $M[i][j]$ is value of E2E performance from IDO i of AS_1 to IDO j of AS_N, with the directional AS sequence being the E2E AS level path.

There are two prerequisites must be satisfied before inter-AS performance calculation:

Prerequisite 1: Performance aggregate calculation can only be implemented on a continuous directional AS sequence. For a directional AS sequence $<AS_1, AS_2, \ldots, AS_N>$, it is a continuous one $\Leftrightarrow$

$$(AS_1 \neq AS_N) \wedge \forall i(1 \leqslant i \leqslant N-1) \rightarrow AS_i\ \delta\ AS_{i+1}$$

Where δ is the relationship that representing neighboring.

Prerequisite 2: Performance metric described must be aggregatable, i.e. the overall performance can be figured out through step-by-step aggregation on partial performance. For an E2E performance metric, it is aggregatable $\Leftrightarrow$

$$F\ (P_1 + P_2 + \ldots + P_N) = F\ (P_1) + F\ (P_2) + \ldots + F\ (P_N)$$

where $F(P_i)$ is the performance mapping, which maps a path into an E2E performance value. $P_1 + P_2 + \ldots + P_N$ represents an E2E path walking through $P_1, P_2, \ldots, P_N$. For familiar E2E metrics such as delay, loss rate and bandwidth, the prerequisite is satisfied.

If both of the two prerequisites are satisfied, inter-AS performance aggregation can be implemented based on different definitions of performance aggregation function o.

Assumes AS-level topology and directional AS sequence is known, MNPM does following works to calculate Inter-AS PM. For a directional AS sequence $<AS_1, AS_2, \ldots, AS_N>$, PMs are $M_1, M_2, \ldots, M_N$. AS_i connects with AS_{i-1} through IDO IN_i, and connects with AS_{i-1} through IDO OUT_i. Inter-AS PM $M = o\ (M_1, M_2, \ldots, M_N)$, is an $a \times b$ matrix, where a is the number of IDO of AS_1, b is the number of IDO of AS_N. Elements of M are calculated as following:

$$M[p][q] = M_1[p][OUT_1] +^* M_2[IN_2][OUT_2] +^* \ldots +^* M_{N-1}[IN_{N-1}][OUT_{N-1}] +^* M_N[IN_N][q] \quad (1)$$

Operator +* represents performance aggregate operation. It takes different forms for different performance metrics. For additive metric (e.g. delay) it is "+", for multiplicative metric (e.g. loss rate) it is "×", for concave metric (e.g. bandwidth) it is Min.

Similar to AS PM, Inter-AS PM can be used not only to model network performance, but also has practical meaning for network applications. 1. Inter-AS PM describes E2E performance from an AS to another through an AS sequence, which can be input into inter-domain routing algorithms, used to optimize inter-domain routing. 2. Internet can largely be regarded as a hierarchical interconnected structure, each layer is composed of large number of ISPs. When a lower-level ISP wants to interconnect with a higher-level ISP, it has to consider the performance that it can achieve. Through Inter-AS PM between the two ISPs, Lower-level ISP can clearly identify the performance it can achieve from the higher-level ISP, therefore make a right decision.

Above discussion has aggregated internal performance of AS, while the performance of IDC between two neighboring ASes has not yet involved. In order to describe performance information in a consistent way, and erase difference between the description of inter-domain and intra-domain, the performance of IDC is accommodated into AS PM of previous hop. For a directional AS sequence $<AS_1, AS_2, \ldots, AS_N>$, AS PMs are $M_1, M_2, \ldots, M_N$, assumes the performance of IDC between AS_i and AS_{i+1} is m_i, AS PM should be processed as following before implementing performance aggregation operation:

$$M_i[p][q] = M_i[p][q] +^* m_i \quad (2)$$

V. Simulation Research on MNPM

In order to verify whether MNPM is capable of representing performance of large-scale network conveniently and correctly, the network simulator NS2 [17] is used to experiment on MNPM. First, the simulation problem about representing performance of a single AS with MNPM is explored, then the multi-AS performance model involving an AS sequence with MNPM is simulated later, further the E2E performance along the AS sequence is calculated according to the performance aggregation algorithm of MNPM described in Section 3, the calculated results are compared with the E2E performance of this AS sequence that is directly measured to verify the feasibility and correctness of MNPM. In the following, we illustrate the simulation process and use RTT as a performance parameter: (1) Along an E2E path of the AS sequence, Separate Measure (SM) of RTT for each single AS is done respectively. (2) These results are aggregated to represent the RTT of this AS sequence. We call the total result Aggregated Measure (AM). (3) The RTT of this E2E AS sequence is measured directly. We call the result Direct Measure (DM). (4) Finally, the AM RTT is compared with the DM RTT. The simulation processes are as follows in details.

1. *Performance metric and measurement*: RTT is selected as the performance metric. Probes are deployed on each IDO of AS, and send 10 active measurement packets every 10 *sec*. The size of packet is 64 bytes, the interval between packets is Poisson-modulated and the average value is 20 *msec*. Time-out value of each packet is 5 *sec*.

2. *Network topology and traffic pattern:* The network topology is shown in Fig. 2 with 5 ASes. Link bandwidth is 100 *Mbps* and propagation delay is 10 *msec*. Traffic pattern is shown in Fig. 3. In order to simulate the traffic pattern that adheres to that of Internet, backbone traffic is composed of 60 Pareto flows that each average rate is 1*Mbps*. On/off duration of each flow follows Pareto distribution, the average value of on/off duration are both 500 *msec*. Branch traffic within each AS is composed of 20 Pareto flows, average rate is 1*Mbps*, average duration of on/off period is 500 *msec*. The aggregated Pareto flow has the feature of long-range dependence and heavy-tailed distribution, which reflects characteristic of current Internet traffic.

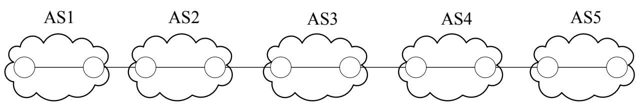


Fig. 2 The Network Topology

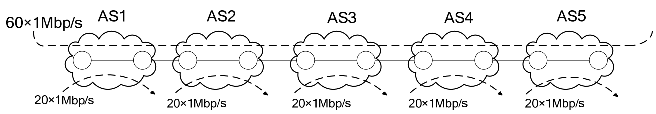


Fig. 3 The Traffic Pattern

3. *Experimental results:* The simulation has lasted 1000 seconds with traffic begins at 100 *sec*, both DM and SM have acquired 100 RTT samples which are shown as the curves in Fig. 4 respectively. Taking the DM result as reference, the AM result is compared with it, and the cumulative distribution function (CDF) of variance of AM against DM is shown in Fig. 5. Notice that the point *A* means variances of 95% measurement results are less than 0.18%, point *B* stands for the largest variance is 1.87%. It is obvious that after aggregation of SM, the value of AM is consistent to that of DM, which verifies the feasibility and correctness of MNPM.

In order to verify whether the experimental results using MNPM depending on AS path length, the simulation has been implemented under AS path length being 10 and 15 respectively besides 5; the corresponding cumulative distribution function of variance is shown in Fig. 6. It is obvious that variance between the values of AM calculated from SM and the value of E2E DM doesn't change noticeably even though AS path length has extended for 2 and 3 times, which indicates the experimental results using MNPM have little to do with AS path length.

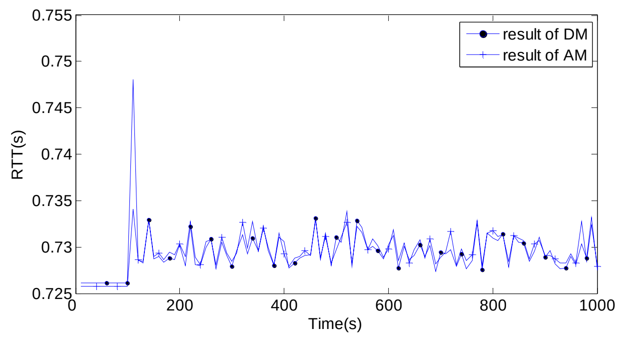


Fig. 4 Measurement result of AM and DM

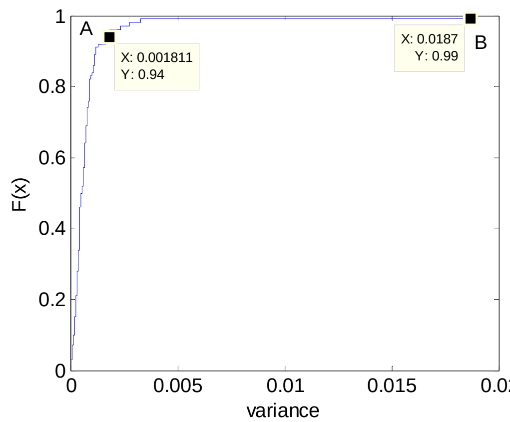


Fig. 5 CDF of variance between AS and DM

VI. Detecting Network Congestion with Value of Determinant of PM

Besides the description of E2E performance between any two IDOs of ASes, MNPM may have many other potential usages. Assume a traffic flow suddenly leaps within an AS, RTT of one or more links within that AS should experience a change sharply, and all the changes must be reflected in determinant of PM accordingly. Generally speaking, abnormity can be identified by comparing the elements of PM under normal condition with those under abnormal condition. However this method has several disadvantages. It is time consuming to identify the normal value of all elements of PM and do the comparison one by one. The original information stored in PM should be processed and expressed in certain kind of metric for the convenience of transmission and storage. From network security point of view, administrators of AS would rather publish a certain metric instead of disclosing the complete PM. Therefore, we define a metric δ_{RTT}, whose value equals to the absolute value of RTT PM determinant. δ_{RTT} is applied to network congestion detection and it works well. Details of the simulation experiment are as following.

1. Router level topology of AS is generated with topology generator GT-ITM [18], Waxman model is used to describe intra-domain topology. It places designated number of nodes randomly on a space room, the probability of existing a link between two nodes *u*, *v* is

$$P(u,v)=\alpha e^{-d/(\beta L)}$$

where α and β are constant, $L=\sqrt{2}*scale$ is the maximum distance between two nodes, and *d* is the geometrical distance between *u* and *v*.

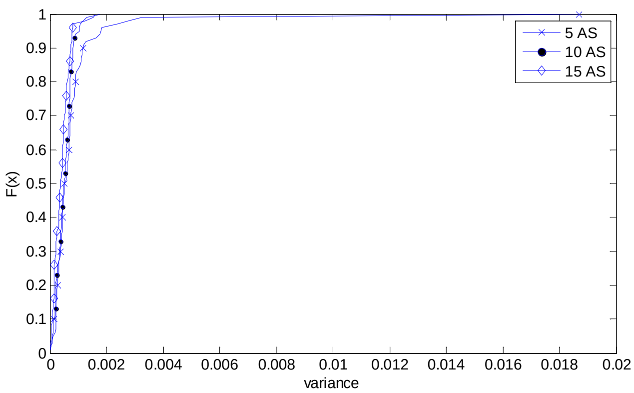


Fig. 6 CDF of variance under different AS length

2. Determine the physical layer property of topology, including queuing disciplines, bandwidth between nodes, and propagation delay. Drop-tail queuing mechanism is used in simulation, link bandwidth is 100 *Mbps* and propagation delay is proportional to geometrical distance of the link.

3. After the generation of router level topology, the number of IDOs and their locations should be designated to determine RTT PM of AS. In order to reflect conditions of AS using PM completely, the locations of IDOs should be dispersive as much as possible. For the convenience of research, the number of nodes within AS is 50, number of IDOs is 4.

4. Shortest path routing protocol is used as intra-domain routing protocol, it minimize the node hop count.

5. Because of its connectionless nature, UDP traffic is used to generate congestion in some specific parts of AS since the sending rate can easily be controlled unlike TCP.

6. The relationship between network congestion and value of metric δ_{RTT} is illustrated in Fig. 7. The congestion between two IDOs chosen randomly is generated on purpose and we can observe the change of value of δ_{RTT}.

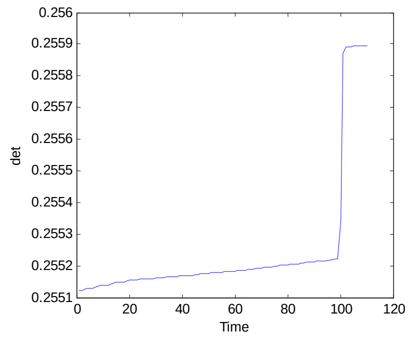


Fig. 7 Metric δ_{RTT} changes with network congestion

In the simulation experiment, network congestion occurs at time 100 in Fig. 7. Meanwhile the value of δ_{RTT} changes greatly at this point, and before this point the value of δ_{RTT} changes slowly and smoothly. It is shown that the metric δ_{RTT} has manifest effect on network congestion, and can be used to judge whether congestion exists in network or not. In simulation, we also generate congestion between several pairs of IDOs simultaneously, similar phenomena as that in Fig. 7 are discovered. It means that metric δ_{RTT} is sensitive to network congestion and can be used to detect network congestion no matter it occurs one place or more places.

VII. Conclusion

With matrix format, Matrix based Network Performance Model exhibits performance metrics obtained by network measurement between inter-domain entrances of an AS, it bypasses the difficult problem that complex internal structure of AS is hard to express. MNPM provide a useful quantificational analysis method for description, design and evaluation of large-scale networks. This model also has other features such as low computation complexity, strong express capability and easy deployment. Besides RTT, we are exploring to use other metrics like loss rate, bandwidth, and some other composite metrics in MNPM, and define other metrics based MNPM. Furthermore, applying MNPM to solve quantificationally problems in the fields of inter-domain routing analyze, load balancing, network management and QoS routing are worth researching.

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