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ORIGINAL PAPER

Analysis on the current and the future Internet structure regarding multi-homed and multi-path routing

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Abstract We analyzed how reliability will be improved by adopting inter-domain multi-path and multi-homing routing when the structure in the Internet changes. We identified the properties of the ideal network structure that will maximize the advantage of multi-path and multi-home routing using mathematical analyses. We focused on how each end-to-end path is built, how many multi-paths exist and how each multi-path consists of multi-path and multi-homing segments. Second, we analyzed the trends in the recent changes in how the Internet is structured from the view point of inter-domain multi-path routing. The mathematical analyses suggest that a large number of multi-paths or multi-homing is not necessary to effectively benefit from multi-path routing. However, it will be important to keep the path length short in the segments where multiple paths are not available. The analyses on the recent changes in the Internet structure suggest that multi-path routing will contribute to improvement of reliability in two different ways. For the autonomous systems away from the Internet core, multi-path routing will improve the reliability by going around the busy Internet core, while it will improve the reliability by distributing network traffic load through the Internet core for the autonomous systems close to the core.

Keywords Multi-path routing · Multi-homing · Inter-domain routing · Reliability · Internet routing · Border gateway routing protocol

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1 Introduction

Border Gateway Protocol (BGP) has been the default routing protocol for routing inter-domain network traffic in the Internet. As a path-vector routing protocol, BGP does not recognize all the links in each route [17]. Each exterior BGP speaker (simply called "BGP router" hereafter) knows only the next hop autonomous system (AS) to a specific destination. Although this property has been known to cause routing loops, there are two other significant problems [16].

The first problem is incapability of multi-path routing. The multi-path routing is a set of routing capabilities. It performs the following three functions. First, it discovers multiple paths available from an origin network to a destination network, where either one or both can be a multi-homed network. Second, it distributes network traffic from an origin network to a destination network over multiple paths. Finally, it performs dynamic load-balancing on the network traffic over the multiple paths. There are two major advantages in multi-path routing. First, it will enhance reliability, since multi-path routing does not depend on a path for data transmission. Multi-path routing sustains data transmission from an origin network to a destination network even when the current network path selected by the existing single-path BGP fails. The second advantage is that it will optimize link bandwidth utilization by dynamically distributing network traffic from over-utilized paths to those that are underutilized.

In the current BGP, even if more than one path exists between two end ASes, only one, no matter how many exist, will be selected for actual payload transmissions at a given time. Another path can be used only when the currently used path is down, but not at the same time. This prohibits multi-path routing, which allows network traffic to flow through more than one parallel path to a destination at the same time [22].

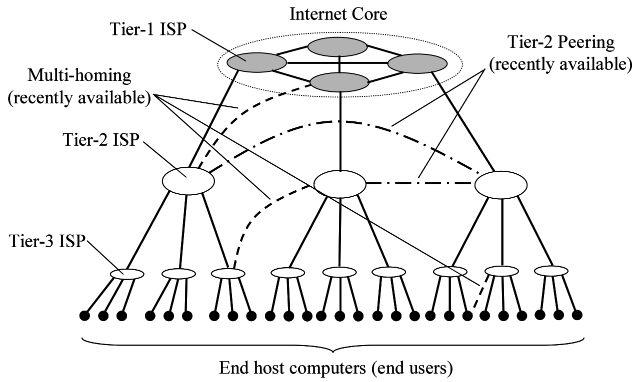

Fig. 1 Simplified AS-interconnection structure in the Internet

Lack of support for multi-path routing has not been a serious problem, since most of the Internet was structured as a tree, where there was not much multi-path routing could do to take its advantages. Figure 1 shows a simplified structure in the interconnections of network carriers in the Internet. The Internet is known to have three layers of tier-1, -2, and -3 Internet service providers (ISPs). Tier-1 layer consists of world-wide "settlement-free" long distance carriers. The ISPs who belong to this group are called "tier-1 ISPs". Tier-2 ISPs are typically continent-wide or even country wide network carriers while tier-3 ISPs are typically regional carriers. It used to be that each tier-2 ISP was connected only to a tier-1 ISP, but not to any other tier-2 ISPs. Thus, only the tier-1 layer used to have a network structure, while others formed "stubs" from the network of the tier-1 ISPs. Despite some differences in details, the terms, "network carriers", "internet service providers", and "autonomous systems" are used interchangeably in this paper, since their differences do not have essential significance in the rest of discussions.

The model shown in Fig. 1 has recently changed. Many tier-2 and 3 ISPs recently added connections to other ISPs in the same layer. This type of connection is called "peering" (shown as dotted links in Fig. 1). Peering has been popularly adopted by content delivery networks to reduce end-to-end delay to their users. Peering invalidates the simple tree structure that has been used as an assumption to not adopt inter-domain multi-path routing in the Internet. Although the deviations from the long-assumed tree structure due to peering have been often discussed in the past, their impacts to the potential of multi-path routing have not been studied enough.

The second problem is lack of BGP's support to multi-path routing to multi-homed networks [4]. Multi-homed networks are tier-3 or -2 ISPs that are connected to more than one higher-layer ISP. When a network transmits its traffic to a multi-homed destination, existing BGP does not allow multi-path routing to multi-homed networks because the existing BGP forwards only the selected best path to other ISPs. Lack of multi-path routing to multi-homed networks is a serious problem even in the cost effectiveness. According to Goldenberg, a full-rate OC3 up-link connection costs $28K to $43K per month and, without an efficient multi-path routing support, having multiple connections will only increase the charge to users in multi-homed networks because the capacity of redundant connections brought by multi-homing will not be efficiently utilized [7].

Multi-path routing has become more important than ever for the following reasons. First, ability to sustain data transmission on link failures becomes critical since many of the Internet users are now business users. Even network down for a few minutes can cause tremendous financial losses to such users. Although BGP is capable of detecting alternative paths and switching to another on a link failure, existing TCP connections will be dropped due to BGP's long convergence delay, which necessitates human end users to restart the transmissions [8, 17]. Network users demand a high level of reliability while accidental wire disconnections, intense denial-of-service attacks, and flash crowds are often causing loss of application-level connectivity. As a result, reliability, as we defined to be the capability to sustain application-level connectivity, is one of the vital factors for data transmission quality.

Second, the traffic load has continued to increase and the network resource is never enough to handle such huge volume of the ever increasing network traffic. Use of multi-path routing can maximize network hardware resource utilization by offloading excess network traffic from over-utilized paths to under-utilized ones. If BGP can dynamically divert burden on some already over-utilized resources to less utilized ones, it will realize Internet-wide load balancing.

Third, Norton argued that the internal structure of the Internet has been changed since its origin, especially in such a way that there exist many multiple paths due to recent peering between tier-2 and -3 ISPs. These changes imply that Internet's structure today can be significantly different from the one that has been the basis of BGP-4 routing protocol. If this is true, multi-path routing can be applied not only to the network of tier-1 ISPs but possibly to the entire Internet [13].

The first objective in this paper is to analyze and quantify how much multi-path routing in the Internet will improve reliability against link failures. To quantify the reliability, we focused on the resilience to link failures. We defined the resilience to link failures as the capability to maintain the connectivity to the Internet when a link failure occurs. We analyzed what factors have significant impact to multi-path routing for maximizing reliability. The second objective is to investigate if the Internet is structured and growing in the ways it can take advantage of multi-path routing. For that objective, we studied how many multi-paths exist between two network domains on average, where such multiple paths exist, and more importantly, what the past trend in the way the Internet's structure is changing *from the viewpoint of multi-path routing*.

The rest of this paper is organized as follows. Section 2 discusses the existing related work on analyzing the structure of the AS interconnections in the Internet. In Sect. 3, we studied major network properties, such as the path length, number of multiple paths, degree of multi-homing and composition of multi-paths, which are expected to have impact to the performance of future multi-path routing in the Internet. In Sect. 4, we identified the trends in the recent changes in how the Internet is structured by examining the BGP UPDATE messages obtained at four observation points for approximately three years. Section 5 summarizes the conclusions, followed by a list of the selected references.

2 Existing related work

The structure of the Internet has been actively studied especially since the mid-1990s [18]. One major area in the study has been modeling the Internet structure by applying graph theory to the structure of AS interconnections [3, 6, 19, 23]. This group of work tries to represent the structure using a few parameters typically used in graph theory, such as degree of connectivity and its distribution. For example, Faloutsos argued that the degree of AS connectivity follows power laws [3]. Zhang developed a technique to improve accuracy of modeling the AS-topology using BGP routing tables obtained from multiple observation points [23]. Subramanian [19] made a step further by developing methods to infer different types of inter-AS relationship, which adds more insight to the structure in the Internet. The concept of multi-path routing [22] and load balancing based on multi-homing [9, 10] have been introduced, but, by the best knowledge of the authors, there has not been a formal study that analyzed the impact of the network topology to multi-path and multi-homing, especially from a view point of enhancing reliability.

Another approach focused on compositions of each end-to-end path [5, 21]. For example, Gao developed a method that infers types of AS interconnection in BGP paths [5]. Oliveira combined the above two approaches to improve the accuracy in modeling the AS interconnections in the Internet by understanding what types of AS interconnection tend to be undetected by BGP routing table scans and why [14].

Some of the recent work focused on dynamisms in the Internet structure. Oliveira studied how ASes and their interconnections were newly created and disappeared [15]. Chang observed increases in establishing peering relations and found that the majority of peering was established through public peering, which is peering through an exchange point, while private peering is a dedicated peering connection between two ISPs [2].

3 Mathematical analyses on the ideal network structure for multi-path routing

In quantifying an expected benefit from adoption of multi-path routing to the Internet, we focused on the reliability in data transmissions. We defined the reliability in data transmissions to be the probability of continuing transmissions on link failures. In multi-path routing, it is the probability that one of the multiple paths between two end ASes survives.

In modeling the multi-path structure that emerges as the results of the existing multi-homing and peering in the Internet today (as shown in Fig. 1), we built a simplified model for our reliability analysis as shown in Fig. 2. The model was built to capture the general structure in a multiple-path routing configuration between two terminal hosts at the same time it is tractable in quantifying reliability using multi-path routing. The model assumes that the transmitting side is a single-home network and that multiple paths exist between the single-home origin network and a multi-homed destination network, which will be a common configuration for many networks in the Internet today.

In the model, node S indicates a source end host computer, while D indicates a destination end host computer. To simplify the model, we assumed that each ISP is represented by an exterior BGP router (thus, R_1 represents an ISP, R_2 does another, and so on). S is subscribed to an ISP and connected to the ISP's router, R_{15}. D is multi-homed to two different ISPs. It is connected to R_1 in its first ISP and to

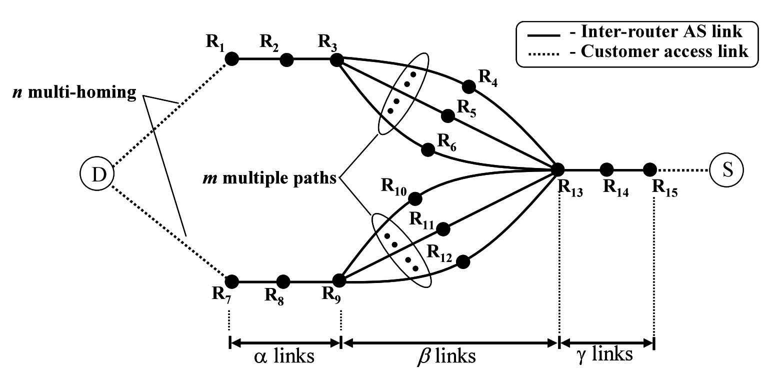

Fig. 2 Model for reliability analysis using multi-path routing to a multi-homed destination

R_7 in its second ISP. Although each ISP can have multiple egress/ingress points to another ISP, we model each ISP as a node, where two ISPs are always connected by an AS link even though there can be multiple AS links between them.

It is assumed that each route from S to D consists of multiple links. We assumed that the term "route" means a logical connection from a source to a destination ISP (thus there are two routes from S to D in Fig. 2: from R_{15} to R_1 and from R_{15} to R_7). The term "link" is defined to mean a logical connection between two exterior BGP routers, thus between two ISPs. Since the two terms, "ISP" and "AS", are interchangeable, we use a term "AS link" for "link". A partial sequence of links within a route is called a "path". For example, there are m multiple paths between R_{13} and R_3 in the route from R_{15} to R_1.

We considered only AS links in our analysis. It is also assumed that a section in a route may have multiple parallel paths as Gao argued [5]. Each route is assumed to consist of three sections. The first section corresponds to the source side's edge links, where there is no multiple path exists (the section is called "source side single-path section" hereafter). The second section is the one where multiple parallel paths are available ("multi-path section"). "Multiple parallel paths" are called "multiple paths" hereafter. The third section corresponds to the destination side's edge links ("destination side single-path section"). Similar to the source side single-path section, the destination side single-path section has only one path (i.e., no multiple path exists).

Based on the above model, the following control parameters are used in our analysis:

- $\boldsymbol{m}$: degree of multiple paths available in the multi-path section
- $\boldsymbol{n}$: degree of multi-homing in the destination side
- $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$: number of AS links in the destination side single path, multi-path, and source side single-path sections, respectively
- $\boldsymbol{p}$: link-failure rate for each link ($0 < \boldsymbol{p} < 1$).

Using the above parameters, the reliability in data transmissions from S to D (called "the reliability" hereafter) is defined as the probability that at least one route survives when each link will fail at a probability of p. The reliability is quantified by

$$\big(1 - \big(\big(1 - \big(1 - \big(\big(1 - \big((1-p)^{\beta}\big)\big)^{m}\big)\big) \times \big((1-p)^{\alpha}\big)\big)^{n}\big)\big) \times \big((1-p)^{\gamma}\big) \qquad (1)$$

We analyzed the reliability for different m, n, and p, while we changed the values of α, β, and γ, as well as their relative ratio for understanding their impact to the reliability.

Analysis #1 ("path length analysis"): The impact of the path length to the reliability was analyzed for different link-failure rates. The reliability was calculated using (1) while a set of α, β, and γ was changed from $(\alpha, \beta, \gamma) = (1, 1, 1)$ to $(6, 6, 6)$. To increase the path length without modifying the ratio of the three sections, the same value was applied to α, β, and γ. For the degree of multiple paths, $m = 4$ was applied. The reliability was calculated for three different cases of $n = 1$ (no multi-homing), 2, and 3. We analyzed the impact using the minimum case $(\alpha, \beta, \gamma) = (1, 1, 1)$ through $(6, 6, 6)$ based on the observation that most of the BGP path length is less than 20 hops [6]. We also applied this assumption to other analyses, Analysis #2, #3 and #4.

Analysis #2 ("length of multi-path section analysis"): The reliability was calculated while the length of multi-path section (β) was changed from 1 to 8 to see the effect of the different ratios of β to α and γ. While β was changed, α and γ remained unchanged ($\alpha = 2$ and $\gamma = 2$ were used). Same as Analysis #1, $m = 4$ was used and the reliability was calculated for $n = 1$, 2, and 3.

Analysis #3 ("degree of multi-path analysis"): This analysis estimates the impact of the degree of multiple paths to the reliability. The expected reliability was calculated for $m = 1$ (no multiple path available) to 8. For (α, β, γ) values, $(2, 2, 2)$ was applied. Similar to the previous analyses, the reliability was estimated for $n = 1$, 2, and 3. For a multi-homed environment (i.e., $n > 1$), the same value of m was applied to each multi-home route to the destination network.

Analysis #4 ("length of single-path section analysis"): The reliability was calculated while the length of the single-path sections (α, γ) was changed. While β was fixed, the values of α and γ were changed from $(\alpha, \gamma) = (1, 1)$ to $(8, 8)$. The reliability was calculated for $n = 1$, 2, and 3. $\beta = 2$ and $m = 4$ were used in this analysis.

3.1 Observations and analysis for Analysis #1

Figure 3 shows the ranges of the link-failure probability (p) that yielded 10%+ improvement in the raw (absolute) dif-

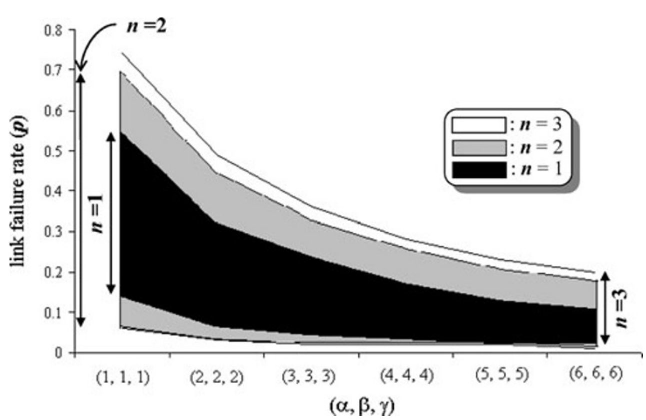

Fig. 3 Ranges of link failure rate (p) that yielded 10%+ improvement in Analysis #1

ference in reliability for the existing single-path BGP routing and for the multi-path routing. For the single-path BGP routing, it was assumed that data transmission using a path fails if any AS link in the path fails, while data transmission fails only if all the m multi-paths fail (i.e., at least one AS link in each of m multi-paths fails). At $(\alpha, \beta, \gamma) = (1, 1, 1)$, the range of p that yielded 10%+ improvement for $n = 1$ (no multi-homing) was $p = 0.14$ through 0.52. For $n = 2$ (multi-homing with degree of 2), it was $p = 0.06$ through 0.69. For $n = 3$, it was 0.06 through 0.74. The range rapidly shrunk when the path length was increased from $(1, 1, 1)$ to $(3, 3, 3)$, followed by gradual, but monotonic decreases to $(6, 6, 6)$. At $(6, 6, 6)$, the ranges of 10%+ improvement were reduced to $p = 0.03$ through 0.11 for $n = 1$, $p = 0.01$ through 0.17 for $n = 2$, and 0.01 through 0.20 for $n = 3$.

The results of Analysis #1 suggest that the path length should be short to maximize the reliability by multi-path routing. The width of p that yielded 10%+ difference for $n = 1, 2$, and 3 at $(\alpha, \beta, \gamma) = (1, 1, 1)$ was 0.38 (0.52–0.14) for $n = 1$, it was 0.63 and 0.68 for $n = 2$ and 3. The ranges of p shrunk to 0.15, 0.30, and 0.34 at $(3, 3, 3)$ and 0.08, 0.16, and 0.19 at $(6, 6, 6)$ for $n = 1, 2$, and 3, respectively. The ratio of p for $n = 1$, 2, and 3 at $(1, 1, 1)$ was approximately 1.0:1.67:1.74, while the ratio was 1.0:2.0:2.26 at $(3, 3, 3)$ and 1.0:2.0:2.4 at $(6, 6, 6)$. These results imply that multi-homing will be more effective in improving the reliability when the path length is longer, while multi-path routing will be more effective when the path length is shorter. Assuming that the ASes away from the Internet core have a longer average path length to other ASes, multi-homing will be an effective technique to improve the reliability for those ASes away from the Internet core, while multi-path routing will be effective for those close to the Internet core.

3.2 Observations and analysis for Analysis #2

Figure 4 shows how the range of p that yielded 10%+ difference between no multi-path and multi-path routing changed when the length of the multi-path section (β) was increased from 1 to 8 while α and γ were fixed at 2. When $\beta = 1$, the ranges of p was 0.04 through 0.44 for $n = 2$, and $p = 0.04$ through 0.50 for $n = 3$. For $n = 1$, the reliability was completely the same as that of no multi-path routing, which validated (1). When $\beta = 8$, the ranges of p were 0.02 through 0.26 for $n = 1$, 0.02 through 0.32 for $n = 2$, and 0.02 through 0.36 for $n = 3$. After $\beta = 5$, β did not significantly affect the ranges of the 10%+ improvement.

The multi-homed networks with degree of two or larger are connected to the Internet backbone using at least two different paths. Therefore, we did not expect that the length of the multi-path section (section β) would have a significant impact to the reliability for such multi-homed networks. That is because such multi-homed networks can switch to a backup link on a failure of their primary access link. Contrary to our prediction, these results suggest that multi-homing will significantly improve the reliability if used with multi-path routing when the length of the multi-path section (section β) is long. These outcomes imply that multi-homed networks that are "distant" from the Internet core will benefit more from multi-path routing, compared to those who are "close" to the Internet core.

3.3 Observations and analysis for Analysis #3

Figure 5 shows how the range of p that yielded 10%+ difference changed when the degree of multi-path was increased from $m = 1$ to 8. When $m = 1$ (no multi-path exists), the ranges were $p = 0.04$ through 0.28 for $n = 2$ and 0.02 through 0.36 for $n = 3$. The single-home configuration resulted in no improvement when $m = 1$ by the same reason for Analysis 2. At $m = 5$, the ranges for $n = 1, 2$, and 3 were 0.07 through 0.33, 0.03 through 0.45, and 0.03 through 0.50, respectively. After $m = 5$, increase in the range was minor (at most 2.4% increase from $m = 5$ to 6 for $n = 2$).

The results indicate that a relatively small number of multiple paths will significantly contribute to improvement

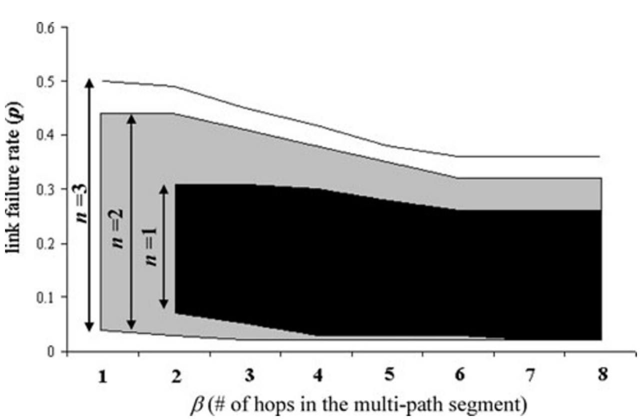

Fig. 4 Ranges of link failure rate (p) that yielded 10%+ improvement in Analysis #2

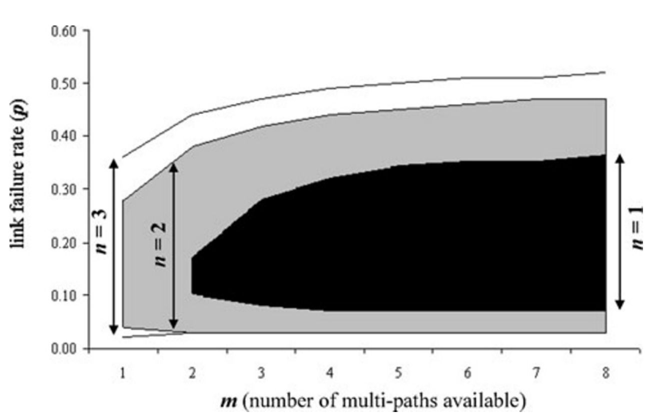

Fig. 5 Ranges of link failure rate (p) that yielded 10%+ improvement in Analysis #3

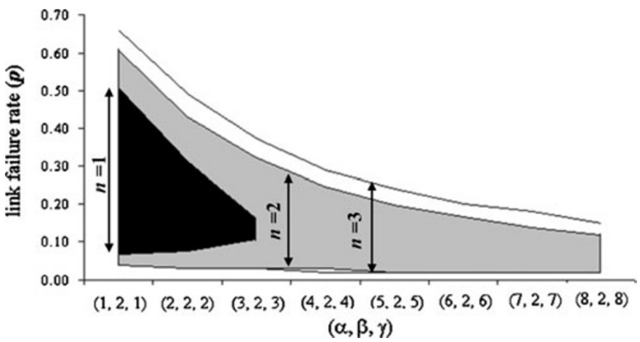

Fig. 6 Ranges of link failure rate (p) that yielded 10%+ improvement in Analysis #4

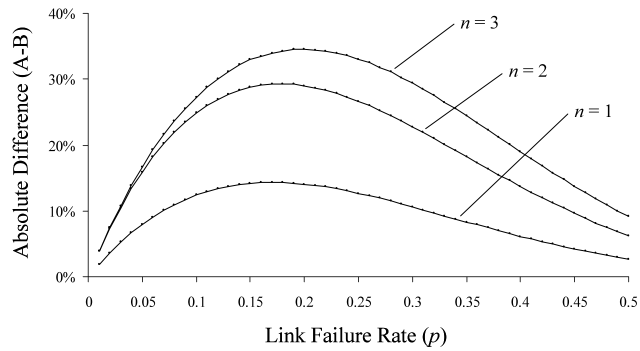

Fig. 7 Absolute differences for the transmission reliability

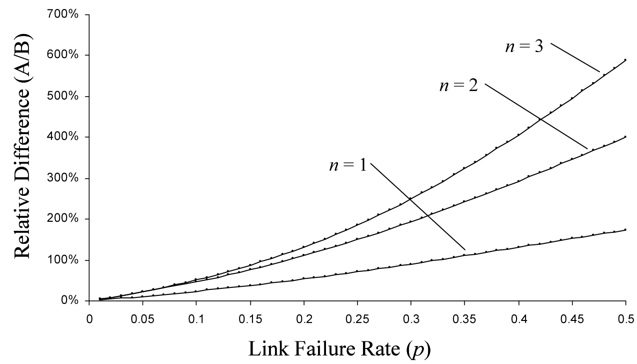

Fig. 8 Relative differences for the transmission reliability

of the reliability. The results also suggest that the reliability will not be improved proportionally when the number of multiple paths continues to increase. For example, from $m = 1$ to 4, the range of p increased for $n = 1$, 2, and 3 by 242.9% (from $m = 2$ to 4 for $n = 1$), 70.8% and 35.3%, respectively, while from $m = 4$ to 8, the increases were only 16.7%, 7.3%, and 6.5%. At and above $m = 4$, the improvement significantly slowed down. These results suggest that a small number (three to four, especially three) of multiple paths will be most cost effective.

3.4 Observations and analysis for Analysis #4

Figure 6 shows the ranges of p that yielded 10%+ difference when α and γ were changed from 1 to 8 (always the same value was assigned to α and γ) while the value of β was fixed to 2. At $(\alpha, \beta, \gamma) = (1, 2, 1)$, the ranges of p were 0.06 through 0.51 for $n = 1$, 0.04 through 0.62 for $n = 2$, and 0.04 through 0.66 for $n = 3$. At $(\alpha, \beta, \gamma) = (3, 2, 3)$ and above, the single-home configuration did not improve the reliability more than 10%. The ranges of p for $n = 2$ and 3 shrunk rather rapidly when α and γ were increased. When α and γ were increased from (1, 2, 1) to (5, 2, 5), the ranges shrunk by 29.3, 26.8, 26.6, and 18.2% each time for $n = 2$. The range shrunk by 25.8, 26.1, 20.6, and 18.5% for $n = 3$. After $(\alpha, \beta, \gamma) = (5, 2, 5)$, the rate of shrink in the 10% improvement ranges slowed down though.

As the length of the single-path sections (α and γ) increased, the advantage of multi-path routing rapidly decreased. When α and γ were four or higher, the range of link-failure rate that produced 10%+ improvement disappeared for the single-homed configuration, while for the multi-homed configurations, the ranges slowly decreased in Fig. 6. These results suggest that the length of the single-path sections (α and γ) should be short if multi-homing is not used. If the length of the single-path sections is relatively longer than that of the multi-path section, multi-homing will be effective to taking the advantages of multi-path routing.

Figures 7 and 8 show the absolute and differences between the reliability of no multi-path routing (noted as symbol "B" in the y-axis) and that of the three multi-homing configurations of $n = 1$, 2, and 3 (noted as "A") for $m = 4$ and $(\alpha, \beta, \gamma) = (2, 2, 2)$ for a range of $p : 0.01 \le p \le 0.50$. The absolute difference ("A–B") was calculated as

$$R_{M(n)} - R_N \tag{2}$$

and the relative difference ("A/B") was calculated as

$$(R_{M(n)} - R_N)/R_N \tag{3}$$

while $R_{M(n)}$ refers to the reliability of a multi-path routing with the degree of multi-homing of n where $n = 1$, 2, or 3 and R_N refers to the reliability of no multi-path routing.

For the three multi-homing configurations of $n = 1$, 2, and 3, the absolute differences were all positive (multi-path routing to a multi-homed destination always resulted in a better reliability). The graph also shows that the relative differences monotonically increased for all the three configurations, although their absolute differences reached a peak while p was between 0.1 and 0.2. The same pattern was observed for all other configurations of m, α, β, and γ tested in Analysis #1, #2, #3, and #4. The only observed differences were in the height of the peaks and the skews in the peaks of the absolute differences.

4 Analyses on the trends in the past changes in the Internet's inter-domain structure

This section describes our analyses on the present state of the existing connections in ASes in the Internet to observe if the past and the current changes in its structure are along the ideal network structure for multi-path routing identified in the previous section. Its primary objective is in understanding the present state of the available multi-path connections in the Internet to observe if the past and the current changes in its structure are along the ideal network structure identified in the previous section.

For the above objectives, we performed two different analyses. In the first analysis (Analysis #5), we investigated how the number of available multiple paths differs for ASes in different locations in the Internet. We counted the number for ASes that are close to the Internet core and ASes that are away from the Internet core. The primary objective in this analysis is to assess who will most or least benefit from future multi-path routing. In the second analysis (Analysis #6), we investigated who are contributing to future multi-path routing and how. We first classified network carriers as tier-1, tier-2, and CATV carriers, and analyzed how much of the existing BGP paths are carried out by which type of carrier. We then observed how the carriers are expanding their BGP peering paths in the Internet. The primary objective in this analysis is to study if the Internet has enough BGP multiple paths to take the advantage of multi-path routing.

We performed the analyses using the AS links extracted from the BGP path update messages collected by Route-Views Project [20]. We used the BGP updates archive from RouteView project, since it publishes the largest existing BGP updates archive. The data sets contained BGP UPDATE messages announced in the global Internet as observed by multiple observation points. Its data sets are also considered one of the most representative archives and many research projects, such as CAIDA's (CAIDA is for the Cooperative Association for Internet Data Analysis) NetGeo and AS Path Visualization funded by the US National Science Foundation, are using the data sets [20].

The path update messages are the information two BGP routers in the Internet exchange to propagate available paths to reach other ASes over the global Internet. Each update message contains the AS_PATH field that contains a sequence of ASes, through which a remote network domain can be reached. For example, in the following example of the AS_PATH field, the AS_PATH field indicates that the BGP router that receives this message can reach a network domain of 146.163.255.255/16 by following the path of AS-920, 701, 4425, and 10854 in that order. The existing ASes in the Internet periodically or dynamically exchange the update messages to advertise the existing paths to other ASes.

146.163.255.255/16 AS_PATH: 920 701 4425 10854

In the above example, two consecutive ASes in the sequence imply that there exists a logical or physical unidirectional link between the two ASes in the global Internet. The existing links are extracted from the update messages and they are used to detect the AS interconnections in the Internet. We used the AS interconnections to understand which AS is connected to other ASes and how they are connected. The data sets we used for the analyses were from EQIX (Equinix), ISC, LINX, and WIDE for the following time windows:

- ISC (route-views.isc.routeviews.org) for January 2004 through November 2008
- LINX (route-views.linx.routeviews.org) for July 2004 through November 2008
- WIDE (route-views.wide.routeviews.org) for September 2003 through November 2008
- Equinix Ashburn (route-views.eqix.route-views.org) as EQIX for October 2005 through November 2008.

We reconstructed a BGP routing table, Adj-RIB-in (Adjacent Routing Information Base, Incoming) table, from the BGP UPDATE messages based on the following concepts:

AS link: For any two consecutive ASes that appear in the AS_PATH field, we assumed that there is an AS link from the former to the latter (in the order of their appearances in the AS_PATH field). Although AS links are unidirectional in the current BGP, we assume that they are bidirectional. We adopted this assumption mainly because the physical connections in each AS link are usually capable of bidirectional transmissions and also because the bidirectional capability most probably will be utilized when multi-path routing is adopted in the future to maximize the benefits of the multi-path routing.

BGP path: Each BGP path is a sequence of one or more AS links from a source AS to a destination AS. We used not only the actual BGP paths but potential BGP paths in discovering multiple paths. The actual BGP paths are those that appeared in the AS_PATH field of Adj-RIB-in table, while the potential paths are those that can be synthesized by combinations of any existing AS links in Adj-RIB-in table.

Multiple BGP paths: Multiple BGP paths are a set of BGP paths that have the same origin and the destination ASes, each of which contains at least one AS link that does not appear in other BGP paths in the set (except for AS-prepending).

The Internet core: The AS that has the largest degree of connectivity in the Internet. It was AS-701 (MCI Communications Services) as of December 2010, which is connected to 1,452 other ASes.

Table 1 List of the analyses performed in Analysis #5

Analysis	Descriptions
$N_{\text{CORE-X}}$	Number of the core ASes detected in data set X (X is "EQIX", "ISC", "LINX", or "WIDE")
$N_{\text{CORE-X}}/N_{\text{CORE-LINX}}$	Percentage of the number of detected core ASes in data set X to that of LINX
$N_{(\text{CORE-X, S-HOP})}$	Number of the core ASes that is away from AS-701 by *S* hops in a data *X*
$(N_{(\text{CORE-X, 1-HOP})} + N_{(\text{CORE-X, 2-HOP})})/N_{\text{CORE-X}}$	Percentage of the core ASes that have one or two hops away from AS-701 in a data set X
$N_{(\text{CORE-X, M-SHORTEST})}$	Number of the core ASes in data set X that have M shortest multiple paths to AS-701
$(N_{\text{CORE-X}} - N_{\text{CORE-X,-1-SHOREST}})/N_{\text{CORE-X}}$	Percentage of the core ASees in data set X that have at least two multiple paths to AS-701
$M_{\text{CDF-X}}$	CDF on the number of the core ASes in data set X that have a particular number of multiple shortest paths to AS-701
$N_{\text{SHORT-EXTRA-L}}$	Number of available multiple paths to AS-701 that are longer than the shortest path by up to L hops

Core ASes: Core ASes are those that satisfy both of the following two conditions. (i) The ASes that have a cycle BGP path using which an AS can reach itself without going through the same AS more than once (except the origin AS) and (ii) The cycle contains AS-701. As a result, with all AS links being bidirectional, the core ASes are those that have multiple BGP paths to the Internet core.

Analysis #5 (BGP multi-path analysis): Availability of multiple BGP paths from an AS to another in the global Internet was analyzed. Table 1 defines and describes the analyses performed on the number of multiple paths from each core AS to the Internet core (i.e., AS-701).

Analysis #6 (ISP classification analysis): In this analysis, each core AS that appears in a BGP path is classified to a tier-1, tier-2, cable-TV (CATV), or other ISP. For Tier-1 and tier-2 ISP's, we used a list of the tier 1 and 2 ISP's published by the Cooperative Association for Internet Data Analysis project [1]. For CATV carriers in the North America, we used a list of the major cable operators in the North America region compiled by National Cable & Telecommunication Association [12].

Based on the classifications, BGP paths from each core AS to the Internet core (i.e., AS 701) are categorized in the following criteria:

- *Tier-1 paths*: the paths that go through at least one tier-1 ISP
- *Non-tier-1 paths*: the paths that do not go through any tier-1 ISP
- *Tier-2 paths*: the paths that go through at least one tier-2 ISP
- *Non-tier-2 paths*: the paths that do not go through any tier-2 ISP
- *CATV paths*: the paths that go through at least one CATV ISP
- *Non-CATV paths*: the paths that do not go through any CATV ISP.

Note that some categories are not antagonistic to each other. For example, a BGP path can be a tier-1 path at the same time it is a tier-2 path, while one cannot be a tier-1 path at the same time it is a non-tier-1 path. Table 2 lists the terms considered in Analysis #6.

4.1 Observations and analysis for Analysis #5

Figures 9 through 14 show the results from Analysis #5. Figure 9 shows the number of the core ASes detected in EQIX, ISC, LINX, and WIDE and their ratio to LINX, which resulted in the largest number of the core ASes. The figure shows the ratio of the core ASes in each data set that can reach the Internet core in one, two, three, and four or more AS-hops using their shortest path. For example, 1.7% of the core ASes detected in WIDE could reach AS-701 using only one hop, 53.1% of them could reach AS-701 using two hops, and so on.

Figure 10 shows the observed cumulative distribution for the number of multiple shortest BGP paths from each core AS to AS-701 in the four data sets. In the figure, the number of multiple paths of zero ("0" on the x axis) means those that have only one shortest path to AS-701. For example, in LINX, 14.0% of its core ASes have only one shortest BGP path to AS-701, while 60.3% of them have up to two additional (i.e., a total of three) BGP shortest paths to reach AS-701.

Figure 11(a) shows the ratio of the number of the core ASes detected in WIDE, ISC, and EQIX to that of LINX, the percentage of the core ASes that are either one or two hops away from AS-701 (based on their shortest paths) to all the detected core ASes in each data set, and the percentage of the core ASes that have at least two shortest paths to AS-701 in each data set. The figure indicates strong correlations among the three statistics, especially between the ratio of the core ASes, and the percentage of the core ASes that are either one or two hops away from AS-701.

The correlations are visualized in Fig. 11(b) with the solid lines indicating their trends. The figure shows that the

Table 2 List of the analyses performed in Analysis #6

Term	Description
N_{TOTAL}	Number of the distinct BGP paths from a core AS to the Internet core (AS-701) detected in each of the data sets (EQIX, ISC, LINX, WIDE)
P_{T1}, P_{T2}, P_{CATV}	The set of the paths detected in a data set that go through at least a tier-1, tier-2 and CATV ISP, respectively
P_{NT1}, P_{NT2}, P_{NCATV}	The set of the paths detected in a data set that do not go through any tier-1, tier-2 and CATV ISP, respectively
$N(P_{T1})$, $N(P_{T2})$, $N(P_{CATV})$	Number of the BGP paths in a data set that go through at least a tier-1, tier-2 and a CATV ISP, respectively
$N(P_{NT1})$, $N(P_{NT2})$, $N(P_{NCATV})$	Number of the BGP paths in a data set that do not go through any tier-1, tier-2, and CATV ISP, respectively
R_{T1}, R_{T2}, R_{CATV}	$= N(P_{T1})/N_{TOTAL}$, $N(P_{T2})/N_{TOTAL}$, $N(P_{CATV})/N_{TOTAL}$
R_{NT1}, R_{NT2}, R_{NCATV}	$= N(P_{NT1})/N_{TOTAL}$, $N(P_{NT2})/N_{TOTAL}$, $N(P_{NCATV})/N_{TOTAL}$
$N(P_{T2} \cap P_{NT1})/N(P_{T2} \cap P_{T1})$	Ratio of the tier-2 paths without going through a tier-1 ISP to the tier-2 paths that go through a tier-1 ISP
$N(P_{CATV} \cap P_{NT1})/N(P_{CATV} \cap P_{T1})$	Ratio of the CATV paths without going through a tier-1 ISP to the CATV paths that go through a tier-1 ISP

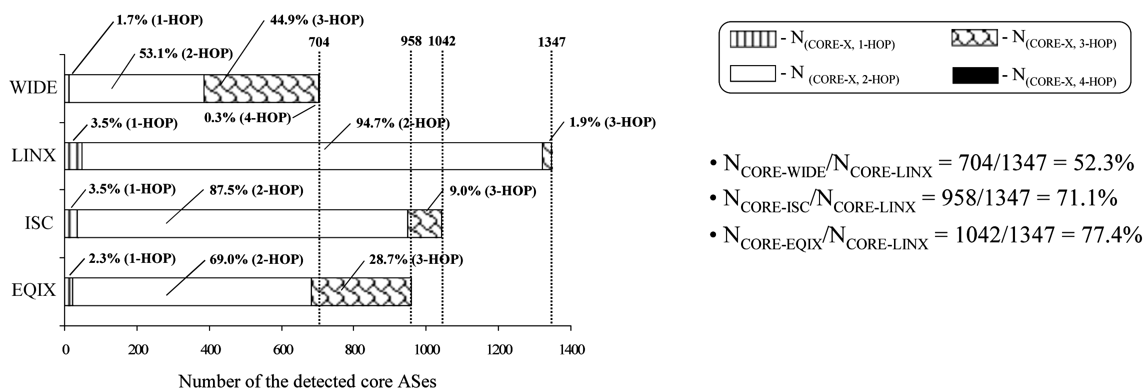

Fig. 9 Number of detected core ASes in each data set ($N_{CORE\text{-}X}$) and composition of BGP paths with different path length ($N_{(CORE\text{-}X,\ S\text{-}HOP)}$ for $S = 1, 2, 3$ and 4)

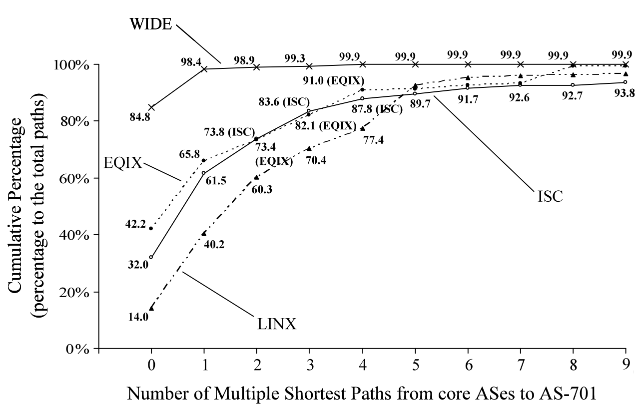

Fig. 10 Observed CDF for the number of multiple shortest BGP paths to AS-701 (M_{CDF})

percentage of the core ASes which are close (in terms of AS interconnections) to the Internet core (those that reach the core in one or two AS links) proportionally increased when the number of the core ASes increases. The figure also shows a similar result for the percentage of the core ASes that have at least two shortest paths to the core of the Internet.

Figures 12 and 13 show the number of multiple shortest paths, those with one extra hop over the shortest path, and two extra hops, from each core AS to AS-701 in EQIX and WIDE. Their y-axis shows the number of the core ASes in each data set. The logarithm of base 10 is applied to the y-axis for EQIX (but not for WIDE). ISC and LINX showed a similar result as EQIX. The number of detected multiple paths increased by an order of magnitude each time the hop count was relaxed by one over the shortest path for EQIX, ISC, and LINX, while the numbers increased much slower in WIDE.

Figure 14 shows the number of, multiple shortest paths, multiple paths with one extra hop over the shortest paths,

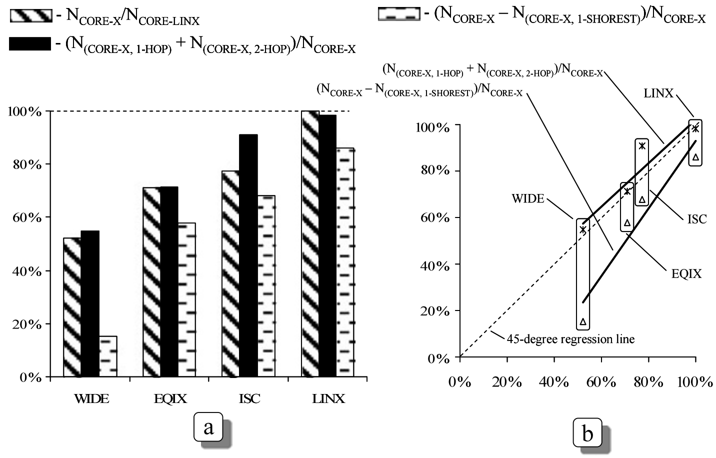

Fig. 11 (**a**) and (**b**)—Observed correlation in the three analyses

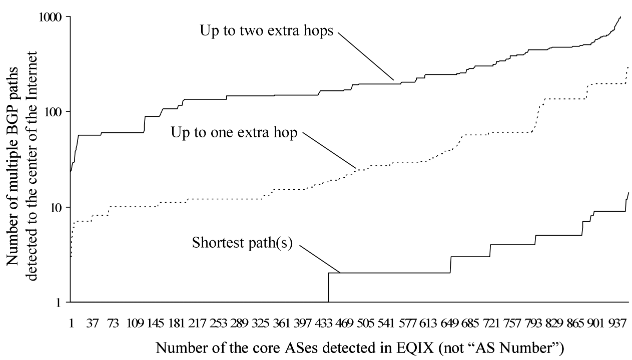

Fig. 12 $N_{SHORT\text{-}EXTRA\text{-}L}$ for $L = 1, 2, 3$ in EQIX

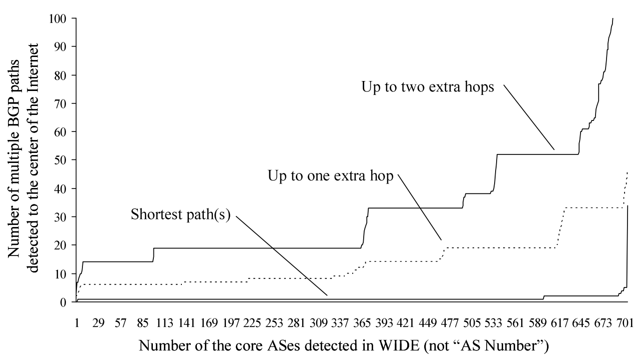

Fig. 13 $N_{SHORT\text{-}EXTRA\text{-}L}$ for $L = 1, 2, 3$ in WIDE

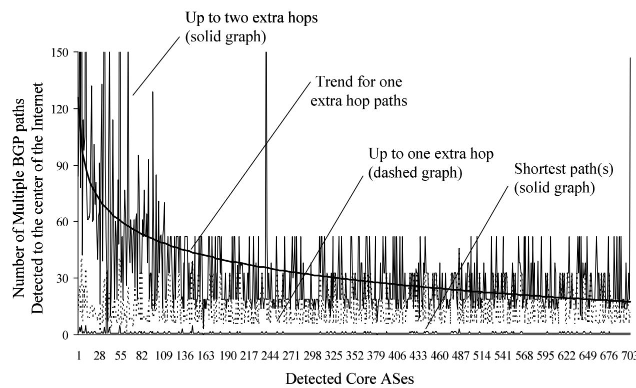

Fig. 14 Number of multiple BGP paths in WIDE, ordered in the ascending AS numbers

and those with two extra hops, from each of the core ASes to the Internet core (i.e., AS 701) in WIDE (the plots over 150 on the y axis are not shown). In the figure the core ASes are sorted on the x-axis in the ascending order of their “AS number”. The trend line is for the number of the paths with one extra hop.

The graphs show that the core ASes with a small AS number tend to have more multiple BGP paths than those with a large AS number. It is likely that the ASes with a low AS number are those that participated in the Internet in its early stage and that they occupy the majority of its core. The above observations, which are consistent with the power law predicted by Faloutsos [3], indicate uneven distribution of AS links.

We speculated on why the numbers of detected core ASes are different in the four data sets to understand what the correlations of the three statistics in Fig. 11(b) mean. One of the possible ways to explain the correlation is as follows. At each AS, BGP-4, as a path-vector routing protocol, propagates only the selected best path to each destination to other ASes. In this process, when an AS propagates BGP UPDATE messages, the messages will go through more intermediate ASes before they reach ASes that are far away from the Internet core. As a result, many multiple BGP paths to each destination will be filtered out at intermediate ASes, while only the selected best paths will be forwarded farther to other ASes. With less multiple BGP paths advertised to other ASes, the number of the core ASes will be reduced too.

Figure 15 shows an example that demonstrates the phenomenon described above. Seven ASes are connected as shown in the figure. When AS 701 advertises itself in the network, the four ASes of AS 1, 2, 3, and 4 become core

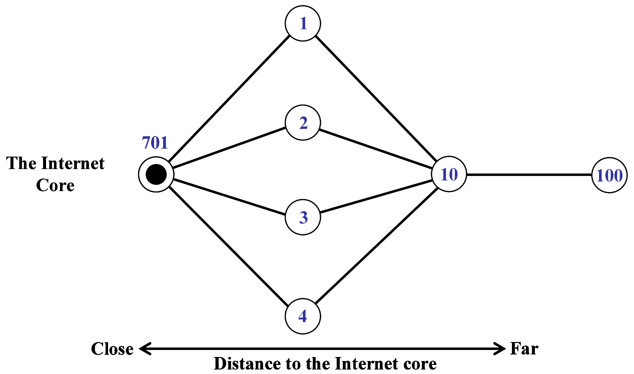

Fig. 15 An example of AS connections that demonstrates reductions of the core ASes

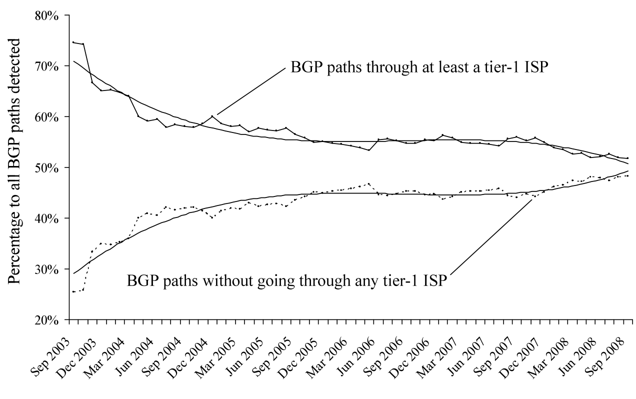

Fig. 16 Ratio of the tier-1 BGP paths (WIDE)

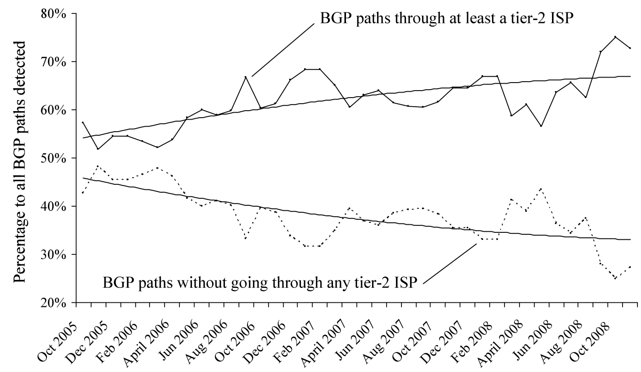

Fig. 17 Ratio of the tier-2 paths (EQIX)

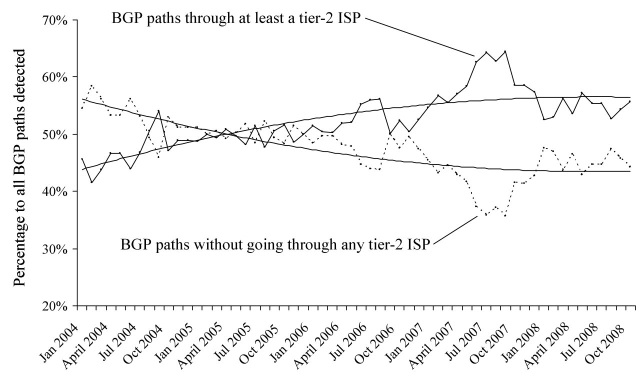

Fig. 18 Ratio of the tier-2 paths (ISC)

ASes, since each of them will have a cycle that contains AS 701, assuming that each AS link is bidirectional. For example, AS 1 will have three cycles 1-701-2 (3, 4)-10-1 and it will detect four core ASes. The same will happen to AS 2, 3, 4, and 10. However, since AS 10 propagates only its selected best path for AS 701 to AS 100, AS 100 will detect only two core ASes of AS 10 and (1, 2, 3, or 4). If this hypothesis is correct, ASes far away (i.e., more hops to the Internet core) will have fewer core ASes. This can also explain the results in Figs. 9, 10, and 11.

If the above hypothesis is correct, the results shown by Figs. 9 through 13 can be considered as the aftermaths of filtering multiple paths at intermediate ASes before they are propagated to those away from the Internet core. The ASes that have a larger number of multiple shortest paths to the Internet core are considered to be those "closer" to the Internet core. For example, LINX is the one closest to the Internet core, followed by ISC, EQIX, and WIDE.

4.2 Observations and analysis for Analysis #6

Figures 16 through 25 show the results of Analysis #6. Figure 16 shows how the ratio of the tier-1 paths (R_{T1}) and the ratio of the non-tier-1 paths (R_{NT1}) in WIDE has changed in the past. The ratio continuously decreased over the past years, and only 52.1% of its BGP paths are currently going through a tier-1 ISP. The trend in the graph suggests that the majority of its BGP paths will most probably bypass the tier-1 ISPs in the near future. Although it was in WIDE that the trend was most clearly observed, a similar result was observed in other three datasets of EQIX, ISC, and LINX. In EQIX, ISC, and LINX, 38.9, 36.2, and 37.7% of their BGP paths are not using a tier-1 ISP.

Figure 17 shows the ratio of the tier-2 paths (R_{T2}) and the ratio of the non-tier-2 paths (R_{NT2}) in EQIX, in which the tier-2 paths already dominated. The ratio continues to have increased in the recent years (75.1% of its BGP paths go through a tier-2 ISP in October 2008). Figure 18 shows that the ratios of the tier-2 paths and the non-tier-2 paths in ISC inversed around April 2005. In ISC, 55.7% of its BGP paths go through a tier-2 ISP in October 2008. We observed a similar result in LINX, where 61.9% of its BGP paths go through a tier-2 ISP in May 2008 and inversion of the ratio happened at the end of 2004. In WIDE, although the majority of its BGP paths are still non-tier-2 paths, its ratio continued to increase in the recent years. In September 2008 the ratio was 30.3% (Fig. 19).

The results in Figs. 16 through 19 show that, although each data set indicates different progress in adopting tier-2

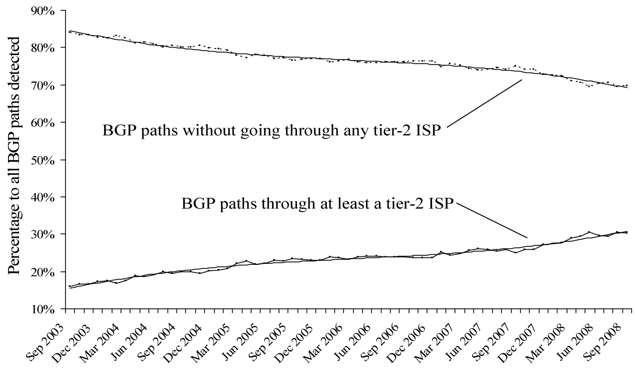

Fig. 19 Ratio of the tier-2 paths (WIDE)

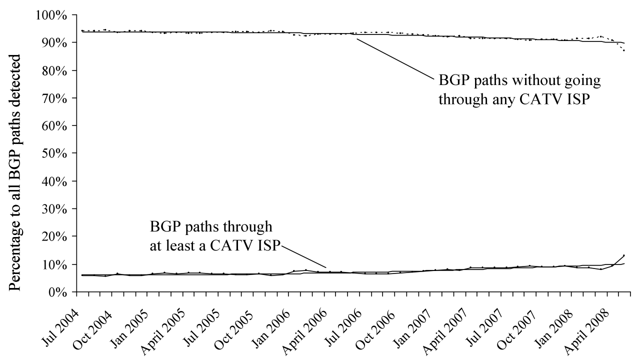

Fig. 20 Ratio of the CATV paths in LINX

paths, the availability of tier-2 paths is steadily increasing in the four data sets. Especially from the hypothesis resulted from Analysis #5, it seems that the progress of adopting tier-2 paths is faster for those that are closer to the Internet core (EQIX, ISC, and LINX), meaning that more tier-2 paths will be available to the ASes closer to the Internet core than those away from the Internet core (WIDE).

Figure 20 shows the ratio of the CATV paths (R_{CATV}) and the ratio of the non-CATV paths (R_{NCATV}) in LINX. Although the ratio is still quite low (13.0% in May 2008) compared to its tier-2 paths, the ratio has been steadily increasing. Quite similar results are also observed in WIDE (7.4% in September 2008). EQIX and ISC showed a similar pattern except that a sudden increase in the ratio occurred (9.4% and 23.4% in October 2008, respectively).

Figure 21 shows the ratio of the tier-2 paths without going through a tier-1 ISP to the tier-2 paths that go through a tier-1 ISP ($N(P_{T2} \cap P_{NT1})/N(P_{T2} \cap P_{T1})$) in WIDE. The figure shows that 82.2% of its tier-2 paths bypass the tier-1 ISPs. In ISC (Fig. 22), the majority of its tier-2 paths still go through a tier-1 ISP, but its ratio is gradually, but constantly decreasing. The ratio has decreased from 80.0% in January 2004 to 57.6% in October 2008. EQIX and LINX showed an opposite pattern, but the tier-2 paths that do not go through any tier-1 ISP currently occupy the majority in both EQIX

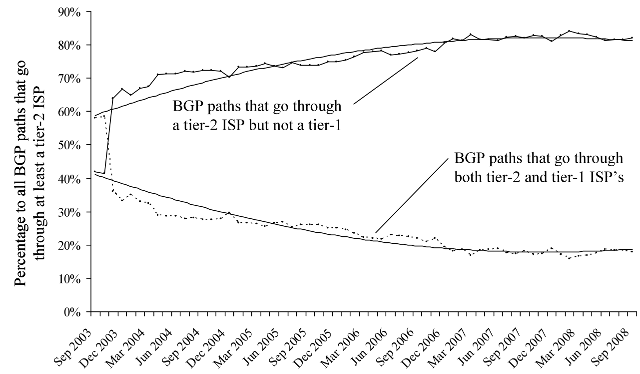

Fig. 21 Ratio of the tier-2 paths without going through any tier-1 ISP to the tier-2 paths that go through a tier-1 ISP in WIDE

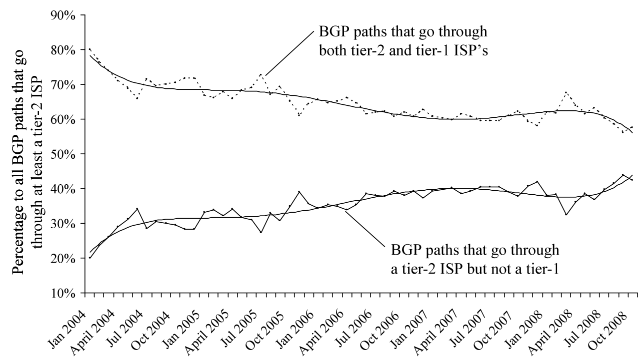

Fig. 22 Ratio of the tier-2 paths without going through any tier-1 ISP to the tier-2 paths that go through a tier-1 ISP in ISC

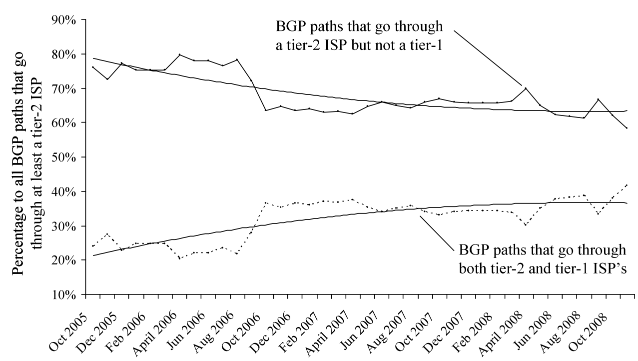

Fig. 23 Ratio of the tier-2 paths without going through any tier-1 ISP to the tier-2 paths that go through a tier-1 ISP in EQIX

(58.2%) and LINX (58.5%). Figure 23 shows the results of EQIX.

Based on the hypothesis from Analysis #5, Figs. 21, 22, and 23 show that the closer an AS is to the Internet core, the more tier-2 peering links exist for them, while Figs. 17, 18, and 19 show that the closer an AS is to the Internet core, the more paths go through a tier-1 ISP. These observations imply that fewer tier-2 paths are available to the ASes away from the Internet core, but more of them are through tier-2

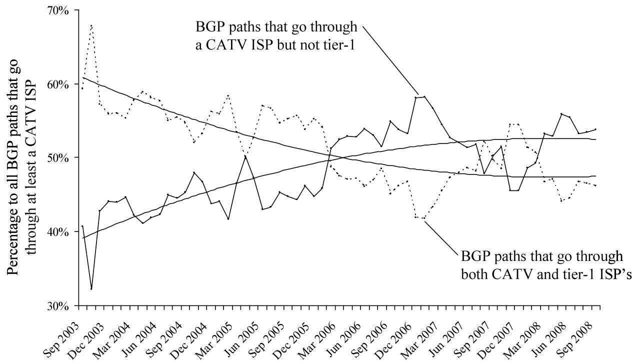

Fig. 24 Ratio of the CATV paths without going through any tier-1 ISP to the CATV paths that go through a tier-1 ISP in WIDE

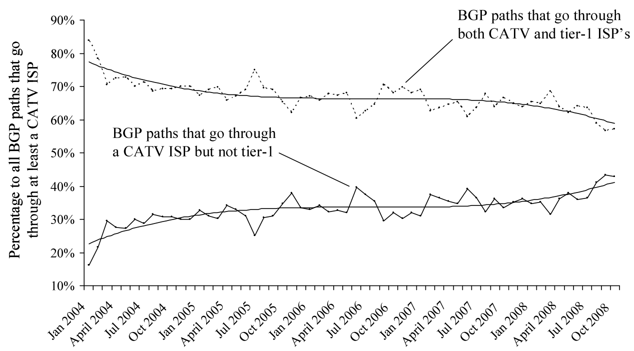

Fig. 25 Ratio of the CATV paths without going through any tier-1 ISP to the CATV paths that go through a tier-1 ISP in ISP

peering links that bypass the tier-1 ISPs. What this means is that for the ASes away from the Internet core, more tier-2 peering links bypass the tier-1 ISPs, which, like the new inter-state highways that go around the center of big (and therefore busy) cities, lets such ASes avoid traffic congestion in the Internet core.

Figures 24 and 25 show the ratio of the CATV paths without going through any tier-1 ISP to the CATV paths going through a tier-1 ISP ($N(P_{CATV} \cap P_{NT1})/N(P_{CATV} \cap P_{T1})$) in WIDE and ISC, respectively. Although the number of BGP paths that go through a CATV ISP is still limited, the two figures suggest that more BGP paths that go through a CATV ISP tend to bypass tier-1 ISPs. LINX showed a similar result to ISC, while EQIX was similar to WIDE. Regarding bypassing tier-1 ISPs, the same tendency appeared in the two figures. For WIDE and EQIX, which are considered ASes away from the Internet core, the tendency of avoiding tier-1 ISPs is more obvious than ISC and LINX, which are ISPs close to the Internet core.

5 Conclusions

The results of the mathematical analyses on the properties of the ideal network structure for multi-path routing brought us the following conclusions. First, to take the advantage of multiple-path routing, the end-to-end path length should be short (from Analysis #1). The results from Analysis #1 also suggested that multi-homing will be an effective technique to improve the reliability for those ASes away from the Internet core, while multi-path routing will be effective for those close to the Internet core. However, these results suggest that multi-homing will significantly improve the reliability if used with multi-path routing, especially when the length of the multi-path section is increased.

Second, the results from Analysis #3 suggest that a large number of multiple paths will not be necessary to take the advantage of multi-path routing. The results showed that three to four multiple paths will be most cost effective.

Third, the length of the single-path sections (α and γ) should be short if multi-homing is not used. Multi-path routing will benefit to multi-homed networks when the single-path sections are relatively longer than the multi-path section (Analysis #4). This means that multi-path routing will be effective for the multi-homed networks away from the Internet core, which manifests an advantage in combining multi-homing and multi-path routing.

Finally, similar to the degree of multiple paths, multi-homing to two ISPs will be most cost effective, since reliability will not be improved proportionally to the increase in the degree of multi-homing over two. The results of our analyses on the recent changes in the Internet's structure are as follow. Although the current inter-domain routing protocol, BGP-4, still assumes a tree structure, the results of our analyses revealed that structure of the Internet today significantly deviates from a simple tree structure. We found that especially tier-2 providers are now playing a significant role in increasing multiple paths, and that many of them bypass the tier-1 ISPs.

The results of Analysis #6 suggest that for the ASes away from the Internet core, more tier-2 and CATV peering bypass the tier-1 ISPs, which means that multi-path routing will effectively let such ASes to avoid traffic congestion in the Internet core, like the new inter-state highways that go around the center of big (and therefore busy) cities. In contrast to the ASes away from the Internet core, more tier-2 and CATV paths are available to those ASes close to the Internet core, meaning that multi-path routing will be effective for such ASes to distribute network traffic through the Internet core, especially when the core is congested.

Despite the growing infrastructure that makes multi-path routing a realistic option and despite the advantages from multi-path routing, security mechanisms that support multi-path routing need to be established. Since network traffic will be spread over multiple carriers using the built-in load-balancing capability in the multi-path routing, which implies that path selections will be less controlled by originating ISP and their customers, it is not hard to imagine that the load-balancing capability will be counter utilized by attacking side, using black-hole routers, bogus BGP path advertises, and DNS hijacking. Another essential future work will be reducing the BGP routing table. At the end of 2010, typical BGP table size approached 300,000 destination prefixes, which made a BGP routing table several hundred megabytes. Huston argued that adoptions of multi-homing are one of the major drivers of the growth [11], which implies that multi-homing is a probable threat to core routers in the future. In order for multi-homing to be popularly adopted in the future, this problem must be addressed.

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