Beyond Centrality - Classifying Topological Significance using Backup Efficiency and Alternative Paths

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***Abstract*— In networks characterized by broad degree distribution, such as the Internet AS graph, node significance is often associated with its degree or with centrality metrics which relate to its reachability and shortest paths passing through it. Such measures do not consider availability of efficient backups of the node and thus often fail to capture its contribution to the functionality and resilience of the network operation. In this paper we suggest the Quality of Backup (QoB) and Alternative Path Centrality (APC) measures as complementary methods which enable relevant analysis of node significance considering backup efficiency. We examine the theoretical significance of these measures and use them to classify nodes in the Internet AS graph applying the BGP valley free restriction on routing. We show that both node degree and node centrality are not necessarily evidence of its significance. In particular, some medium degree nodes with medium centrality measure are shown to be crucial for efficient routing in the Internet AS graph.**

I. Introduction

The topological study of networks appears in a wide spectrum of research areas such as physics [3], biology [10], and computer science [12]. In research of the Internet, node significance classification has received attention in past studies [11], [17], [4], [5] and treated in two different contexts: study of the Internet resiliency against attacks and failures [3], [13], [14], [8] and identification of the Internet core nodes and significance categorization [17], [5]. Both study threads were conducted at the Internet AS level graph.

Several attempts have been made in the past to characterize the core of the Internet AS graph. In [17] the most connected node was used as the natural starting point for defining the Internet's core. Other ASes were also classified to four shells and tendrils that hang from the shells, where ASes in shells with a small index are considered more important than ones in higher indices. Further work has dealt with classification of nodes into a few shells with decreasing importance [9], [16]. In recent study [5] k-shell graph decomposition was used to classify nodes by importance to roughly 40 layers of hierarchal significance. The k-shell classification, based on the node's connectivity, identified over 80 ASes as the Internet core, some of which with medium degrees. Almost exclusively, an attempt to rank ASes by other metrics than node degree was done by CAIDA [1], where the 'cone' of the node has been used to determine its importance, namely the number of direct and indirect customers of the AS.

As network functionality is often measured by connectivity and vertex distances in the graph used as its model, measures which credit vertices connected to a relatively large number of vertices at relatively short distances are often used as significance indicators [11], [3]. However, inadequate consideration of backup by such measures often overshadows significance in context of its contribution to functionality and resilience of the network. Existence of backup raises question about significance as failure of a node with backup does not effect connectivity and does not increase path lengths in the network and thus effect of failure in such instances is minimal. Furthermore, existence of backup denies exclusivity of the information passing through the node in the network. Since nodes can have backups of different efficiencies measures of backup efficiency and topological significance which consider backup efficiency are crucial for analysis of network functionality.

In this paper, we suggest two complementary measures which capture the node significance to network functionality: the Quality of Backup (QoB) and the Alternative Path Centrality (APC). The QoB measures backup quality of a vertex regardless of its centrality or effect on the functionality of the network, and enables comparing backup efficiency between vertices in the graph as well as between vertices from different graphs and can thus serve as a universal measure for backup. The APC measures functionality which considers both backup quality and centrality of vertices in graphs and thus captures node significance in the network.

Our starting point for the node significance classification problem is examination on levels of theoretical abstraction, and then evaluation of our results on the Internet AS graph. Since failure of a node on the AS level is possible [8] though highly unlikely, applying APC and QoB on the Internet AS graph allows a unique insight to the Internet rather than quantifying effects of failures. On the AS level, centrality which considers backup reveals significance in context of potential information which exclusively passes through a node, and its backup quantifies the dependency of its customers on its transit services. In our study we use APC to identify the most significant nodes in the Internet AS graph, and show that these are not necessarily members of the Internet core. In accordance with properties of APC, it is not surprising that the largest ASes in the core, such as UUNET and Sprint, have also very high APC values due to the large number of customer ASes. However, small networks with poor backup like the French research network RENATAR, and the GEANT and Abiline academic backbones which have degrees as low as 51 (RENATER) and low centrality values, have very high

APC values as well.

The rest of this paper is organized as follows. The next section introduces the QoB and its measure of universal backup efficiency. Section III provides detail of the APC construction and discusses its properties. In Section IV, we discuss adaptations of our methods to Internet AS graph model. Section V holds our analysis of the Internet AS graph using the new measures in comparison to previous works. Finally, we summarize and discuss our work in section VI.

II. Quantifying Backup Efficiency

In this section we discuss the effect of backup on measure of functionality and significance in networks. We continue by presenting the Quality of Backup measure which quantifies backup efficiency.

Backup in Networks

When considering a node's contribution to the functionality of the network in terms of its effect on path lengths and connectivity, backup plays a fundamental role. Trivially, failure of a node v does not effect network functionality when a backup node b connected to all of v's neighbors is available. However, such instances in the network are often rare. A more common scenario is one where a v has several nodes connected to a subset of its neighbors, reached at various path distances by nodes leading to v. It is therefore clear that backup of a node may be distributed in the network and vary in efficiency.

The quality of backup of a given vertex in the graph is determined by the number of direct children covered by a set of backup vertices, and the efficiency of reaching this set by the set of direct parents. For a vertex $v \in V$, we define the set of children C_v, set of parents P_v, and the backup set B_v, as follows:

$$\begin{aligned} C_v &= \{u \in V | (v,u) \in E\}, \\ P_v &= \{u \in V | (u,v) \in E\}, \\ B_v &= \{w \in V | \exists u \in C_v : (w,u) \in E\}. \end{aligned}$$

Clearly, in instances of undirected graphs $C_v \equiv P_v$, and the discussion which follows remains relevant for these instances as well.

To discuss properties of the methods suggested here, we formally define the intuitive concept of backup efficiency in a graph as follows.

Definition 1: Let $G = (V, E)$, and $v \in V$ be a vertex with the set of direct children $C_v \subseteq V$, and the backup set $B_v \subseteq V$. Say that v has a d-DISTANT BACKUP SET OF ORDER k, where $k = |C_v \bigcap (\bigcup_{b \in B_v} C_b)|$ and $d = \max\{\delta_v(u,w) | u \in P_v, w \in C_v\}$.

As the definition above refers to the maximal distance between vertices from the sets P_v and C_v, ∞-distant backup order of a vertex is not necessarily a testament of ineffective backup. A vertex b can be an ∞-distant backup set of order $|C_v|$ of v, reachable by all vertices that reach v, but one. Despite ambiguity that may rise from instances of ∞-distant backup order of a vertex, this definition serves its purpose as it provides simple indication of backup efficiency. The methods suggested here are not effected by this formal obstacle as they consider overall efficiency in terms of alternative shortest paths.

Quality of Backup

We introduce the Quality of Backup (QoB) measure which captures backup efficiency regardless of centrality considerations.

Let $G = (V, E)$ be a directed or undirected graph where V is the set of vertices and E is the set of edges. For $u, w \in V$ let $\delta(u, w)$ denote the shortest path distance between u and w in G. The shortest distance, $\delta(u, w)$, can be calculated by any set of rules, e.g., based on additional annotations on the graph edges, and is not limited to minimum hop. By convention, if u cannot reach v through any path in G, then $\delta(u, v) = \infty$. For a directed graph $G = (V, E)$ as above, and $v \in V$, let P_v be the set of v's direct parents and let C_v be the set of v's direct children. For a vertex $v \in V$, the Quality of Backup of v, denoted $\rho(v)$ is:

$$\rho(v) = \frac{\sum_{u \in P_v} \sum_{w \in C_v} \frac{1}{\max\{\delta_v(u,w)-1,1\}}}{|P_v| \cdot |C_v|}$$

The rational behind this measure is the following. To measure backup efficiency of a given vertex, it is enough to examine the cost of re-routing paths from its set of parents to its set of direct children. Note that $\max\{\delta_v(u,w) - 1, 1\} = \delta_v(u,w) - \delta(u,w) + 1$ for all pairs $\langle u, w \rangle$, where $u \in P_v$ and $w \in C_v$. For $v \in V$, it is easy to see that $\rho(v) = 1 \iff \forall \langle x, u \rangle \in P_v \times C_v \quad \exists w \in B_v : (x, w) \in E \wedge (w, u) \in E$, and that $\rho(v) = 0 \iff \delta_v(x, u) = \infty \quad \forall \langle x, u \rangle \in P_v \times C_v$. Thus, $\rho : V \longrightarrow [0, 1]$, and returns 1 for vertices with perfect backups and 0 for vertices with no backup. Formal implementation of QoB is presented in the figure below.

QoB(v, G)
$\rho \leftarrow 0$
for all $u \in P_v$ **do**
  $\bar{\delta}_v(u) \leftarrow \text{BFS}_v(u, G)$
  for all $w \in C_v$ **do**
    $\rho \leftarrow \rho + \frac{1}{\max\{\delta_v(u,w)-1,1\}}$
  end for
  $\rho \leftarrow \frac{\rho}{|P_v| \cdot |C_v|}$
end for
return ρ

The following theorem shows the QoB measure indeed enables local measurement of a vertex's backup in the graph.

Theorem 1: For $G = (V, E)$, for a vertex $v \in V$ with $C_v \neq \emptyset$, $\rho(v)$ monotonically increases with respect to rise in backup efficiency.

Proof: For $u \in P_v$ and $x \in C_v$, assume that $\delta_v(u, x) = c$ in G, where $0 < c \leq \infty$. Construct G' by adding some edge $e \notin E$, such that $\delta'_v(u, x) = c' < c$. Therefore, $\frac{1}{\delta'_v(x,u)} >$

$\frac{1}{\delta_v(x,u)}$, and it easily follows that $\rho'(v) > \rho(v)$, where $\rho'(v)$ is the QoB measure of v in G'. □

III. Alternative Path Centrality

The above section discusses backup efficiency of a vertex regardless of centrality considerations. In an attempt to quantify significance, note that centrality of a node also plays a vital role - a node which has relatively efficient backup can be crucial to the network functionality due to its high centrality, while a node with poor backup and low centrality can have little effect on functionality in the network. The Alternative Path Centrality (APC) measure presented in this section enables quantifying topological contribution of a node to the functionality of the network as it considers both centrality and backup efficiency.

Given a graph $G = (V, E)$ as above and $u \in V$, the topological centrality measure used here, denoted χ, where $\chi : V \longrightarrow \mathbb{R}$ is:

$$\chi(u) = \sum_{w \in V \setminus \{u\}} \frac{1}{\delta(u,w)}$$

Clearly, $0 \leq \chi(u) \leq |V| - 1 \qquad \forall u \in V.$

For a vertex $u \in V$, the value of $\chi(u)$ depends on the number of vertices connected to u and their distances from it; χ monotonically increases with respect to both centrality and connectivity of the vertex. Thus, in relation to other vertices in the graph, high χ values are obtained for a vertex which is connected to a large number of vertices at short distances. Symmetrically, a vertex connected to a small number of vertices at large distances yields low χ values. These properties make the χ function a favorite candidate for measuring vertices' centrality in the network.

For $G = (V, E)$, The APC value of $v \in V$, denoted $\varphi(v)$ is:

$$\varphi(v) = \sum_{u \in V \setminus \{v\}} \chi(u) - \sum_{u \in V \setminus \{v\}} \chi_v(u)$$

Where χ_v denotes centrality values calculated in the graph using alternative paths which bypass v.

The rational behind APC is simple. In instances where network functionality is determined by shortest paths and connectivity, the significance of a node v to the network's functionality can be measured by its effect on these criteria. Computing the difference between vertices' topological centrality using v, and using shortest paths bypassing v enables witnessing v's exclusive contribution to the network's functionality.

The algorithm presented below is a simple implementation of APC using the Breadth First Search (BFS) algorithm for unweighted directed graphs. Here, BFS_v denotes the BFS algorithm which bypasses a vertex v. Both versions return $\bar{\delta}(u)$, the vector of distances from u to all the graph vertices.

Calculating χ and χ_v requires is done in $O(|E|)$ by using BFS. As calculating φ requires $O(|V|)$ activations of the χ calculation, the overall complexity is $O(|V| \cdot |E|)$.

```
APC(v, G)
φ ← 0
for all u ∈ V\{v}  do
    δ̄(u) ← BFS(u, G)
    χ ← 0
    for all w ∈ V\{v, u}  do
        χ ← χ + 1/δ(u,w)
    end for
    δ̄_v(u) ← BFS_v(u, G)
    χ_v ← 0
    for all  w ∈ V\{v, u}  do
        χ_v ← χ_v + 1/δ_v(u,w)
    end for
    φ ← φ + χ − χ_u
end for
return  φ
```

For weighted graphs, one can substitute the BFS algorithm with a single-source shortest path algorithm for non-negative weighted graphs, such as Dijkstra's algorithm [6] with $O(|V| \cdot (|V| \cdot \log |V| + |E|))$ running time. In work done by Demetrescu *et al.* [7] a deterministic oracle is suggested which enables shortest paths queries in instances of node-link failures in $O(1)$ time. Such oracles can be constructed in $O(|E| \cdot |V|^2 + |V| \log |V|)$ time using $O(|V|^2 \log |V|)$ space. In their work, an oracle which is constructed in $O(|E| \cdot |V|^{1.5} + |V|^{2.5} \log |V|)$ and $O(|V|^{2.5})$ space is also presented. In instances where the graph can be preprocessed, such an oracle can be used to compute APC values of all vertices on weighted directed graphs in $O(|V|^2)$ running time.

The following theorem shows that APC properly considers both centrality and backup of a vertex in the graph.

Theorem 2: For $G = (V, E)$ and $u \in V$, $C_u \neq \emptyset$ $\varphi(u)$ monotonically increases with respect to rise in topological centrality and decrement in backup efficiency.

Proof: To prove $\varphi(u)$ monotonically increases with respect to rise in centrality, let $\chi(u) < |V| - 1$, and $w \in V$ be a vertex for which $1 < \delta(u, w) \leq \infty$. Let $e \notin E$ be some edge for which $\delta'(u, w) < \delta(u, w)$, where $\delta'(u, w)$ denotes shortest path distance in $G' = (V, E \bigcup \{e\})$, and e does not create new alternative paths to w in G', as otherwise backup efficiency increases. We show that $\varphi(u) < \varphi'(u)$, where $\varphi'(u)$ denotes the APC value of u in G'. For all $x \in V$, which reach w through v, $\delta'(x, w) < \delta(x, w)$ and $\delta'_v(x, u) = \delta'_v(x, u)$. It therefore follows that $\varphi(u) < \varphi'(u)$.

To prove monotonic increase with respect to decrement in backup efficiency, without loss of generality, assume $|B_u| = 1$. Otherwise, it is easy to show that every graph G, has such a graph $G' = (V', E')$ for which $\exists b \notin V : (x, w) \wedge (w, v) \in E \iff (x, b) \wedge (b, v) \in E' \quad \forall x \in V \quad \forall w \in B_u \quad \forall v \in C_u$ and $\varphi(u) = \varphi'(u)$. We show that $\varphi(u)$ monotonically decreases with respect to rise in k and decrement in d. As rise in k is equivalent to decrement in d for $d = \infty$, it is enough to show that $\varphi(u)$ monotonically decreases with respect to decrement in d.

Assume that $v \in C_u$, and $(w,v) \in E$. Since $B_u = \{w\}$ and $d > 1$, there is some $x \in V$ for which $\delta(x,v) = \delta(x,u) + \delta(u,v)$, and $\delta(x,v) < \delta_u(x,v) \leq \infty$. Let $e \notin E$, be some edge which enables a path from x to w of length $l < \delta(x,w)$, and let $G' = (V,E')$, where $E' = E \bigcup \{e\}$. For $\varphi'(u)$ denoting the APC value of u in G', we show that $\varphi'(u) < \varphi(u)$. As $\delta_u(x,v) = \delta(x,w) + \delta(w,v)$ it follows that $\delta'_u(x,v) < \delta_u(x,v)$, and $\frac{1}{\delta'(x,v)} - \frac{1}{\delta'_u(x,v)} < \frac{1}{\delta(x,v)} - \frac{1}{\delta_u(x,v)}$. It trivially follows that $\varphi'(u) < \varphi(u)$, and concludes proof of the theorem. □

IV. Adaptation of APC and QoB for the directed AS graph

To apply QoB and APC on the Internet, we have adjusted these measures to conform to the model of the AS graph and specifically to the routing restriction which it imposes. We begin with a brief description of the AS graph model.

The Internet AS Graph

The Internet today consists of tens of thousands of networks, each with it own administrative management, called autonomous systems (ASes). Each such AS uses an interior routing protocol (such as OSPF, RIP) inside its managed network, and communicates with neighboring ASes using an exterior routing protocol, called BGP. The graph which models inter-connection between ASes in the Internet is referred to as the Internet AS graph. Since the ASes in the Internet are bound by commercial agreements, restrictions are imposed on the paths which may be explored. The commercial agreements between the ASes are characterized by customer-provider, provider-customer and peer-to-peer relations. A customer pays its provider for transit services, thus the provider transits all packets to and from its customers. The customer, however, will not transit packets for its provider. Specifically, a customer will not transit packets between two of its providers, or between its provider and its peers. Peers are two ASes that agree to provide transit information between their respective customers.

In pioneering work, Lixin Gao [9] has deduced that a legal AS path may either be an *up hill* path, followed by a *down hill* path, or an *up hill* path, followed by a peering link, followed by a *down hill* path. An *up hill* path is a sequential set, possibly empty, of customer-provider links, and a *down hill* path is a sequential set, possible empty, of provider-customer links. Therefore a legal route between ASes can be described as a *valley free* path. A peering link can be traversed only once in each such path, and if it exists in the path it marks the turning point down hill.

The ASQoB and ASAPC Measures

Since connectivity is not transitive in the AS graph, the QoB requires two cardinal adjustments to maintain relevance. Consider the AS graph G=(V,E), and some $v \in V$, for which we wish to obtain $\rho(v)$ in G. Let $u \in P_v$ and $w \in C_v$. The first adjustment is to consider the pair $\langle u,w \rangle \iff u$ can reach w through v using a legal AS path. Description of our second adjustment follows the clarification of its motivation.

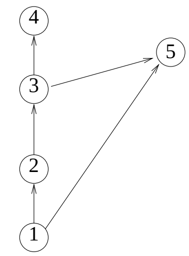

Fig. 1. Illustration of an instance in an AS graph where a direct child can be reached through a backup vertex, though its paths cannot be used. Here, AS 5 serves as a backup for AS 2. Due to exclusiveness of down path between AS 5 and AS 3, AS 1 cannot reach AS 4 via AS 5.

Consider the following instance illustrated in Fig. 1. Suppose a vertex $u \in P_v$ has reached a vertex $w \in C_v$ through an *up - up* path through v, though using the vertex $b \in B_v$, u now reaches w through an *up - down* path. All $x \in C_w$ which are reached through an up path, are now unreachable to u as this creates an illegal AS path. Therefore, to factor this into the QoB measure on the AS graph, we use the following strategy. For all vertices $w \in C_v$ we scan for vertices $x \in C_w$ which are reachable from v through legal AS paths, and consider the pairs $\langle u,x \rangle$ as well. The ASQoB algorithm is described in the figure below. We denote by R_{uv} the set of reachable children of v from u in accordance to policy based routing in the AS graph.

ASQoB(v, G)
$\rho \leftarrow 0$
for all $u \in P_v$ **do**
  $\bar{\delta}_v(u) \leftarrow$ ASBFS$_v(u, G)$
    for all $w \in R_{uv}$ **do**
      $\rho \leftarrow \rho + \frac{1}{\max\{\delta_v(u,w)-1,1\}}$
      for all $x \in R_{vw}$ **do**
        $\rho \leftarrow \rho + \frac{1}{\max\{\delta_v(u,w)-1,1\}}$
    end for
  $\rho \leftarrow \frac{\rho}{\sum_{u \in P_v} \sum_{w \in R_{uv}} |R_{uv}| + |R_{vw}|}$
end for
return ρ

Drawing its strength from the properties of the QoB measure above, the ASQoB remains faithful to the principles of measuring backup efficiency on the AS graph. For $v \in V$, as reachable children are scanned in two levels, we are guaranteed that for $\rho(v) = 1 \iff$ v has a perfect backup which does not disqualify legal AS paths.

Applying APC on the AS graph is straight forward. The calculation of a shortest path, δ, is done using the valley free routing and all the properties discussed in section III hold.

V. Analyzing the directed AS graph

We used the combined data from the DIMES [15] and RouteViews [2] projects for week 11 of 2006. The AS graph is comprised of 20,103 ASes and 57,272 AS links. We approximate the AS relationship by comparing the k-core

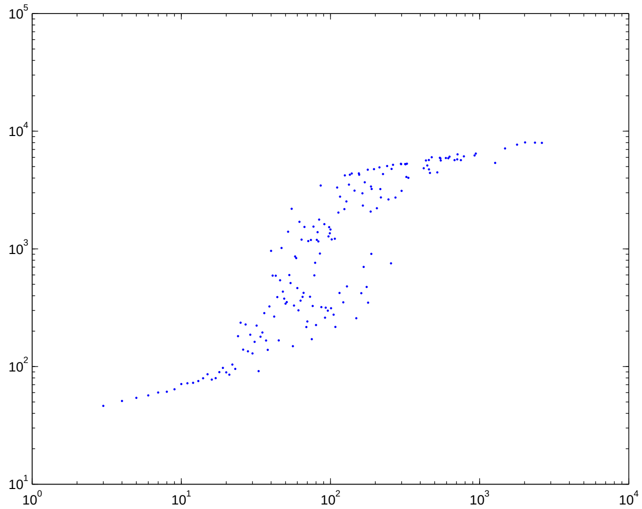

Fig. 2. Average Centrality as a function of its degree.

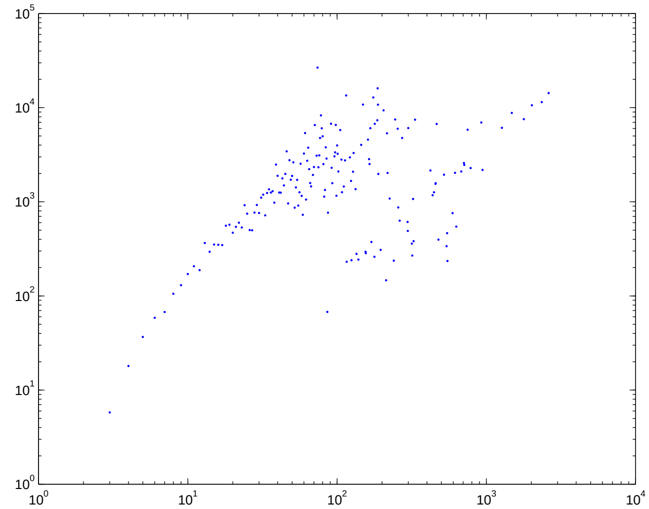

Fig. 3. Average APC as a function of its degree.

index [5] of two ASes and taking the one with the highest k-core index as the provider of the other. If the k-core index is the same the ASes are treated as peers. While we are aware that our approximation introduces some inaccuracies, there is no known error free algorithm for this task. Since the majority of the interesting ASes are within the range of AS numbers 1-22000, we present results of these 11407 ASes along with results of ASes with degree higher than 40 of the rest of AS graph.

We first show that while centrality is closely related to the node degree in the AS graph, our APC criteria captures significance which is not necessarily associated with high degree. Fig. 2 shows the centrality values of AS nodes averaged by their degree on a log-log scale. There is almost a monotonic increase in centrality with degree for nodes of degree above 300, and the close relation between centrality and degree is evident. On the other hand, Fig. 3 shows there is a clear monotonic (and fairly linear in the log log scale) increase in the average APC value from degree 3 up to around 40, and above this value the number of nodes with the same degree is below 10. Therefore any one 'outlayer', namely a node with extreme high or low APC values, can change the average significantly.

To view the relationship between high centrality and high APC values we plot the degree and APC values of the nodes with the highest centrality (Fig. 5) and the degree and centrality of the nodes with the highest APC values (Fig. 4). The five ASes with the highest degree, 701 (UUNET), 7018 (AT&T), 1239 (Sprint), 3356 (Level3), and 174 (Cogent), are also the five ASes with the highest centrality. These are the largest tier-1 providers. In contrast, only UUNET is in the top ten APC list; Sprint and Cogent have also high APC values. These three tier-1 providers support many stub ASes but have relatively low backup measure (0.7–0.75) which explain their high APC values. Level3, which has high centrality, has low APC value because it has a rather high QoB around 0.82. This means that although Level3 (3356) plays a central role in Internet routing, it can be easily replaced by alternative routes and thus is not as important as the previous three nodes. The next nodes with high centrality are 3549 (GBLX), 2914 (Verio), 7132 (SBC), 6461 (Abovenet), and 12956 (Telefonica). These are all tier-1 providers or major providers in Europe.

For nodes with highest APC the picture is different: while UUNET (701) has the fourth largest APC value, many of the high locations in the list are captured by medium sized ASes with poor (and sometimes extremely poor) backup. Through study of the QoB distribution in the AS graph we have learned that there is a large concentration around 1, which is a testament of perfect backup. The median QoB value is 0.9799, and a large majority of the nodes have QoB values above 0.95. The nodes in places 1, 3, and 8 in the top APC list are educational networks, GEANT (20965) in Europe, ENA (11686) in the USA, and Renater (2200) in France (Abiline the US research network was in place 11). The other group of nodes is of medium size providers, France Telecom (3215), YIPES (6517), Ukraine Telecom (6849), and ServerCentral (23352), each appears to have high APC to a different reason. France Telecom, YIPES and UKR Telecom have extremely low QoB, while ServerCentral connect remote locations that might not have efficient alternative paths. Statistics of nodes with highest APC values are displayed in table I.

Fig. 6 shows the distribution of the APC values (note the truncation of the first column). The APC distribution is shown to have a long but narrow tail with only a few nodes with very high APC values, these nodes are scattered almost over the entire degree range, starting with nodes with degree just above 50 (see Fig. 4 and Table I).

The QoB distribution shown in Fig. 7 has a large concentration around 1, which is a testament of perfect backup. The median value is 0.9799, and as the histogram shows a large majority of the nodes have QoB values above 0.95.

Table II shows the top ten nodes in the CAIDA ranking [1] based on the number of customers a node has. The list

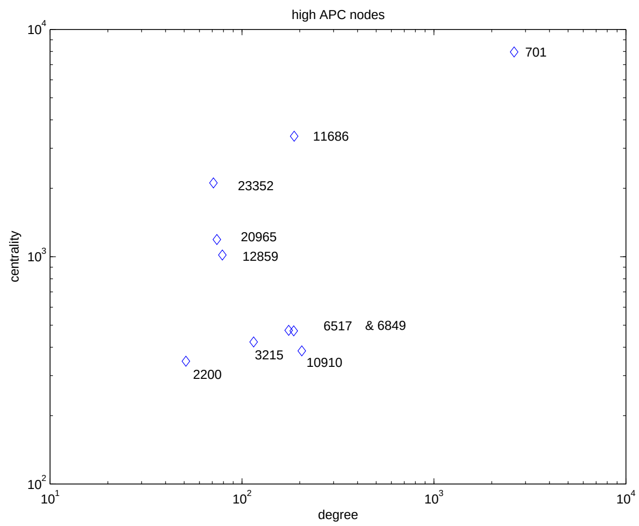

Fig. 4. The degree and centrality of the nodes with the highest APC values.

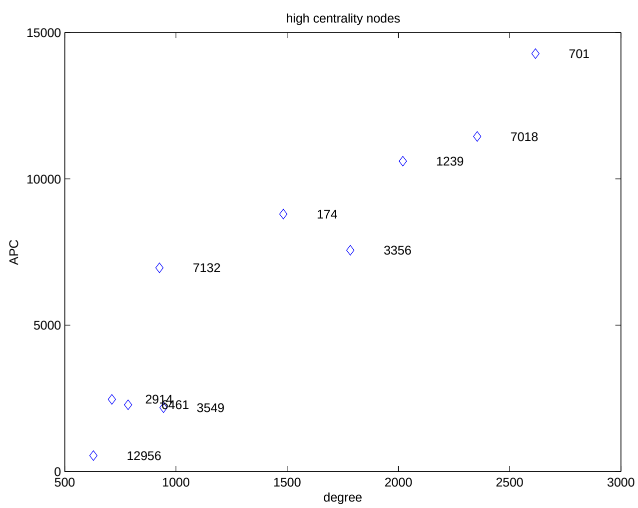

Fig. 5. The degree and APC of the nodes with the highest centrality values.

is dominated by high degree nodes, the two medium degree nodes in the list have also rather high APC values; in general all the nodes have relatively high APC values, eight of them are in the top 38 APC nodes. All the nodes in the list have poor QoB values, possible because of relatively large stub ASes connecting to them. It is vivid that the centrality of the nodes in the CAIDA list is much larger than on our APC list. While all the nodes identified as important in the CAIDA list have high APC values, the opposite is not correct. Several of the nodes in our top 10 list are ranked below place 200 in the CAIDA list.

VI. Conclusions

We have shed light on the contribution of backup efficiency for the node significance classification problem. Given our theoretical analysis, we believe this contribution has merit in classification of network nodes in other fields outside the data networking domain.

AS No.	degree	centrality	QoB	APC
20965	74	1190	0.78569	26628
10910	205	385	0.59486	16298
11686	187	3389	0.92396	16042
701	2616	7956	0.72485	14276
3215	115	422	0.80346	13493
6517	175	474	0.83178	12851
6849	186	472	0.55888	12765
2200	51	347	0.49988	12549
12859	79	1017	0.93949	12396
23352	71	2113	0.94272	12065

TABLE I

Statistics of AS nodes with highest APC values

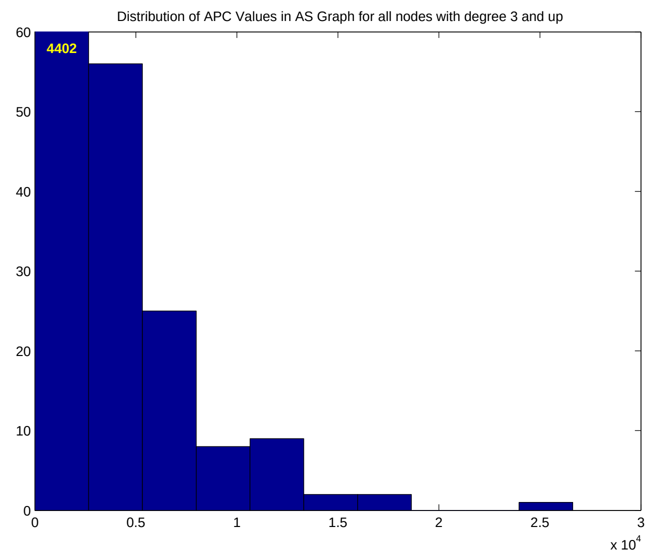

Fig. 6. A histogram of the APC values for nodes of degree greater than 2. The first bin holds 4402 ASes and was truncated.

We are aware that our results are not accurate for several reasons. First, as we stated in the main text, our AS relationship approximation is not accurate. Second, although we used the most detailed Internet map available through the DIMES project, the graph itself is still missing many links which can effect the calculation of all the measures, as well as the AS relationship deduction.

In the future we intend to broaden this research to study the effect of the failure on the PoP level as well as study relationship of sets of nodes in the AS graph in the context of backup and functionality. On the theoretical level, we intend to study the robustness of the APC and QoB measures to error in measurements, as well as well as further formal analysis of their properties.

References

[1] CAIDA AS ranking. http://as-rank.caida.org/.

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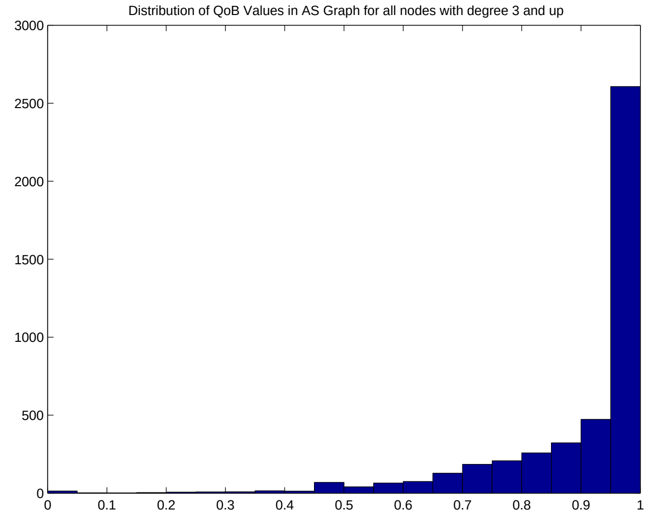

Fig. 7. A histogram of the backup values for nodes of degree greater than 2.

AS No.	degree	centrality	QoB	APC
3356	1784	7690	0.82461	7559
209	1272	5381	0.72495	6113
7018	2354	7992	0.73799	11448
1239	2020	8022	0.7406	10604
701	2616	7955	0.72485	14276
3561	708	5762	0.79559	2579
174	1483	7144	0.76246	8797
703	216	1441	0.86435	10539
19262	188	905	0.75381	10763
702	680	5672	0.77039	2101

TABLE II

STATISTICS OF AS NODES WITH HIGHEST CAIDA SIGNIFICANCE RANKINGS

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