Measuring the Efficiency of Network Designing

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Abstract. Network designing often involves two significant yet contradictive objectives: enhancing the whole network's transmission efficiency while at the same time lowering the whole network's designing cost. Deep study of the interplay between major aspects of network planning–network topology, routing algorithm and node's transmission capability configuration–reveals that good tradeoff can be achieved between these two objectives. By properly combining network topology, routing algorithm and node capability configuration scheme, the network can achieve desirable transmission efficiency at very low cost. This discovery will undoubtedly provide insight into the next generation data network designing.

Keywords: network designing, designing cost, network transmission efficiency, network designing efficiency.

1 Introduction

The Internet becomes more and more complex and susceptible to congestion today. With the emergence of new applications and fast growing population in need of data communication, most experts agree that the existing data network architecture is severely stressed and approaching its capability limits. Thus the move to a brand new next generation data network is in urgent need today.

However, before starting this move, several questions should be properly answered. First, what is the problem with the current data network designing? Second, how to compare between different network designing strategies? Finally, can the network be designed in a cost-effective way and achieve high extensibility.

The answer to the first question requires a close look at the current Internet topology and routing algorithm being used. It has been found that shortest path routing algorithm, which is widely used across Internet literature, has poor performance on BA like networks [1]. Our previous work also found that the most realistic Internet router-level model to date–HOT model–is insensitive to routing algorithm changes, and the only way to improve its transmission efficiency is to upgrade key nodes [2]. In general, when considering network transmission efficiency, network topology, routing algorithm and node capability configuration are closely related to each other. The second question calls for a way to compare and balance the tradeoff between different aspects of network designing

J. Zhou (Ed.): Complex 2009, Part I, LNICST 4, pp. 503–513, 2009.

in a uniform way. For instance, although upgrading critical parts in a network can improve the whole network's transmission efficiency, either economic cost or technical bottleneck will prevent this approach from being used without limitation. That is, either the cost of high-end super computers will exceeds the investment budget or the required processing capability cannot be met due to state-of-art technology constrains. In fact, the network designing can be considered as a multiple objective optimization process. We develop a uniform metric, the network's designing efficiency index(DEI), which reasonably integrates all major designing objectives and simplifies the evaluation process. The answer to the last question can be valuable or insightful to serve as the guidelines for future data network designing. Actually, we find such cost-effective designing schemes do exist.

The rest of this paper is structured as follows: Section 2 provides a brief description of related work. Section 3 introduces the traffic flow model we use. The network designing efficiency index is introduced in section 4 and detailed analysis based on this is given in section 5. Finally, we conclude this paper in section 6.

2 Related Work

Traffic dynamics has been studied extensively on regular networks [3, 4, 5], such as two-dimensional lattices or Cayley trees. However, recent studies on network topologies show that real networks can by no means be characterized by regular networks or random networks [6], but display more complex structural properties such as power-law degree distribution [7, 8]. In Internet router-level topology modeling, two models proposed recently have gained a lot of attentions: BA model [7] and HOT model [9]. BA model is a general model to reproduce the power-law degree distribution by two dynamic mechanisms: growing network and preferential attachment. HOT model more appropriately resembles the real Internet router level topology. It partitions the routers into three hierarchies: the first hierarchy represents the network core, consisting of a number of interconnected low degree nodes with high capabilities, the second hierarchy consists of those high degree access routers connecting to the core routers, and the last hierarchy consists of the low degree peripheral routers connecting to those access routers.

In view of recent evidence that the Internet and many other realistic networks are complex to a significant extent, studies of traffic dynamics on complex network topologies have attracted substantial attentions in recent years [1, 10, 11, 12, 13, 14]. What connects the static network topology and the dynamic traffic behavior is the betweenness centrality. It has been found that if at each time step, R packets with random source and destination addresses are injected into the network and each node can forward only one packet, then the critical packet injection rate R_c can be estimated by

$$R_c = \frac{N(N-1)}{B_{max}} \tag{1}$$

where N is the size of the network and B_{max} is the largest betweenness centrality value of the network [12]. This relationship is intuitive in that the node with the largest betweenness centrality is more susceptible to packet congestion and congestion in this node will quickly spread over the network. Thus, it generally implies that congestion can easily occur in heterogenous networks such as BA network with uniform node transmission capability because in these networks, some nodes have extremely high betweenness centrality values.

With the aim of alleviating traffic congestion and improving the network's transportation capability, three different kind of solutions are proposed. Node heterogeneity is considered in [13], where influences of two node capability models on the traffic dynamics are investigated. A node's capability, i.e, number of packets a node can forward at each time step, is proportionate to its degree and betweenness centrality respectively in these two models. As a conclusion, they suggest a way to alleviate traffic congestion by making nodes with large betweenness as powerful and efficient as possible for processing and transmitting information. The second approach is to change routing algorithms [1]. Instead of following the path with smallest number of links between two nodes as conventionally does, the proposed *efficient routing* algorithm selects a route that minimizes the overall sum of node degrees along it. As the authors have demonstrated, the performance of this routing strategy on BA-like network can be improved over an order of magnitude. The last kind of approach is to modify the network topology. A straightforward way is to improve R_c by creating new edges in the network [15, 16]. A somewhat interesting approach proposed in [14] enhances the BA network's transmission efficiency by kicking out those black sheep edges, i.e, eliminating those edges linking nodes with high betweenness values.

However, from a network designer's perspective, network designing is a multiple objective optimization process. On one hand, it is desirable to achieve high network transmission capability, while on the other hand, it is preferable to lower the cost or the required technology. Unfortunately, these two objectives often contradict with each other. How to design a network in a cost-effective way is thus of significant value. Currently, to the best of our knowledge, all current work strive to optimize the network transmission efficiency, R_c, completely ignoring the lowering of designing cost.

3 Traffic Flow Model

In our traffic flow model, nodes in a network are considered to be capable of generating, forwarding and receiving packets. The traffic dynamics is modeled as follows: at each time step, some packets are injected into the network according to *packet injection mode* and each node forwards some packets according to each node's *transmission capability* towards their destinations based on the particular *routing algorithm*. Each node has a queue for receiving new arriving packets. Packets are processed and transmitted in a first-in-first-out(FIFO) manner so that a packet will be added to the end of the queue when there are other packets waiting for transmission. Once a packet reaches its destination, it is removed from the network.

The above traffic flow model models the traffic dynamics in a network by four constituents: packet injection mode, node transmission capability mode, routing algorithm and queue. Among these four factors, packet injection mode, node transmission capability mode and routing algorithm together determine whether a network will get congested or not. Queue, although affects the network's dynamic behavior, has no influence on whether a network will get congested or not. Therefore, in the following reasoning, we always assume that queues are infinite. And for simplicity, we limit our discussion to the random packet generation mode, i.e, each packet is generated with random source and destination addresses.

4 Measuring a Network Designing Strategy

Since the network designing has two contradictive objectives, we propose a parameterized metric–designing efficiency index(DEI)–to quantitatively measure a designing strategy's efficiency as follows:

$$DEI = \frac{Network\ \ Transmission\ \ Capability}{(Designing\ \ Cost)^{\alpha}} \tag{2}$$

This metric is intuitively reasonable. If two networks have the same designing cost, then the one with higher network transmission capability outperforms the other. Else, if the network transmission capability is fixed, then the one with lower designing cost should be favored. The α here controls the weight each designing objective places in a particular network designing procedure. For example, if α=0, then we can only consider to optimize the network transmission capability, totaly ignoring the designing cost. The exact metrics we choose to represent network transmission capability and designing cost will be discussed in the following two subsections.

4.1 Generalized R_c Computation

Following previous studies, we choose R_c to measure a network's transmission capability, however, to study the network transmission capability for different combinations of network topology, routing algorithm and node capability model, we must extend the computation of R_c to more general context.

In the most generalized case, we have a network topology G, in which each node i can forward $C(i)$ packets at each time step. we no longer assume shortest path routing algorithm, but in stead allow any *topology-based* routing algorithm Γ. By topology-based routing algorithm, we refer to those routing algorithms that only make routing decisions on static topology information, not on dynamic traffic variation.

Since routing algorithm is no longer shortest path routing, betweenness can no longer be used to estimate the possible traffic a node needs to handle at each time step. In this sense, we should replace $B(i)$ with the effective betweenness $B_\Gamma(i)$ to estimate the possible traffic passing through a node, which is formally defined as:

$$B_\Gamma(i) = \sum_{u \neq v} \frac{\delta_\Gamma^{(i)}(u, v)}{\delta_\Gamma(u, v)} \tag{3}$$

where $\delta_\Gamma(u, v)$ is the total number of candidate paths between u and v under routing algorithm Γ and $\delta_\Gamma^{(i)}(u, v)$ is the number of candidate paths under routing algorithm Γ between u and v passing through i.

Based on this definition, at each time step, the expected number of packets arriving at node i in free-flow state is $\frac{RB_\Gamma(i)}{N(N-1)}$. For i not to be congested, it follows that $\frac{RB_\Gamma(i)}{N(N-1)} \le C(i)$, which leads to $R \le \frac{C(i)N(N-1)}{B_\Gamma(i)}$. Therefore, for the whole network to be in free-flow state, the critical injection rate is:

$$R_c = min_i \frac{C(i)N(N-1)}{B_\Gamma(i)} \tag{4}$$

4.2 Designing Cost

In order to study the influence of different node capability assignment strategies on the whole network's transmission efficiency, we fix $\sum_i C(i)$ to be a constant. Thus this sum can no longer be chosen as the network's designing cost. In response, we choose the maximum node capability C_{max} to be the designing cost. This is meaningful for two reasons. First, because low-end servers are very cheap today, a network's financial cost is largely determined by high-end servers. Second, designing cost also refers to technology cost. The required maximum node capability defines the boundary of whether the proposed designing strategy is technically feasible according to state-of-art technologies.

5 Experimental Studies

In this section, we will propose several possible network designing strategies by combining different designing components, and study their designing efficiencies to find some cost-effective designs.

5.1 Routing Algorithms

We employ two routing algorithms: one is the traditional shortest path routing, the other is the efficient routing algorithm proposed in [1]. For given source and destination, the efficient routing algorithm chooses a path that minimizes the sum of node degrees along the path. More formally, the efficient routing chooses a path $s = v_0, v_1, v_2, \cdots, v_k = t$ between s and t that minimizes the objective function $\sum_{0 \le i < k} d(v_i)$, where $d(v_i)$ is the vertex degree of v_i.

5.2 Network Topologies

We apply the above two routing algorithms to six network topologies: ring, lattice, E-R [6], W-S [17], BA and HOT. The ring is constructed by placing all the nodes in a circular ring and connecting each node to its left two nearest nodes and right two nearest nodes. The two-dimensional lattice is constructed in toroidal mode so that the lattice is completely homogeneous. W-S graph is

Table 1. Elementary topological properties of the six networks

Network	Number of Nodes	Number of Edges	Diameter	Average Path Length
Ring	1225	2450	306	153.5
Lattice	1225	2450	34	17.5
WS	1225	2450	14	7.44
ER	1225	2480	11	4.73
BA	1225	2447	7	4.67
HOT	1225	2442	9	6.46

built from the ring by randomly rewiring 20 percent of its edges. BA graph is constructed according to the standard BA model with $m = 2$ [7]. Finally, the HOT model graph contains an 80 nodes random graph with average degree 6 as its network core, 20 high-degree access routers and 1125 periphery nodes. Basic graph properties of the six networks are presented in Table 1.

5.3 Node Transmission Capabilities

Four node capability models are considered: uniform node capability, degree dependent node capability, betweenness dependent node capability and effective betweenness dependent node capability. In uniform node capability mode, each node has the same packet transmission capability. While for the other three node transmission capability modes, a node's transmission capability value is proportionate to its degree, betweenness and effective betweenness respectively.

In order to compare the effects between different node transmission capability modes, we demand that the total capability of a network remains fixed for all the four node capability modes once the network is given, which we set to the sum of all node degrees for simplicity.

Since the assignment will cause a node's capability to be fractional, we treat the fractional capability as follows. Denote $C(i)$ as the transmission capability of node i, then at each time step, i first forwards $\lfloor C(i) \rfloor$ packets towards their destinations, after which a random number $r \in (0, 1)$ is generated and compared against $C(i) - \lfloor C(i) \rfloor$. If $r < C(i) - \lfloor C(i) \rfloor$, i forwards another packet towards its destination. By this means, a node with capability 1.2 will forward 1 packet with probability 0.8 and forward 2 packets with probability 0.2.

5.4 Network Transmission Capability-R_c

R_c can be obtained by applying Equation 4. For shortest path routing, $B_\Gamma(i)$ is equivalent to $B(i)$. However, for efficient routing, an efficient way for calculating $B_\Gamma(i)$ should be first devised. The key to computing $B_\Gamma(i)$ lies in fast detection of paths between any two nodes i and j that minimize the sum of node degrees along the path. We solve this problem as follows. First, we transform each undirected graph into a directed graph by substituting each undirected edge (u, v) with two directed edges (u, v) and (v, u). Second, for each directed edge (u, v), we associate with it a weight $w(u, v) = d(u)$. Fig 1 gives an example of this transformation

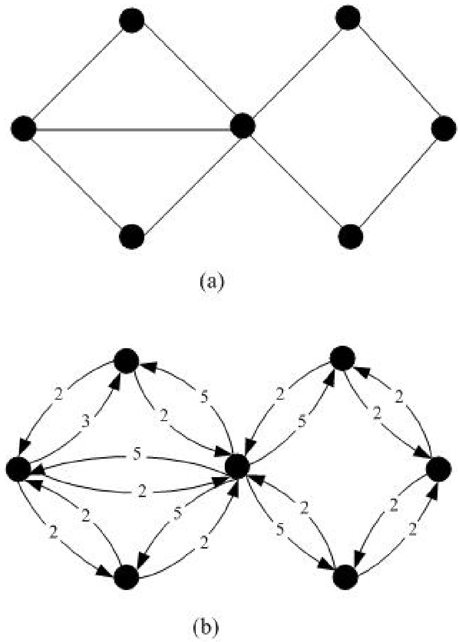

Fig. 1. An example showing how to turn the simple undirected graph into an directed weighted graph for effective betweenness calculation

process. In this way, we turn the problem of finding a path between i and j that minimizes the sum of node degrees into the problem of finding the shortest path between i and j in a directed weighted graph, which can be efficiently solved by Dijkstra's algorithm [18].

Table 2 presents the R_c values for different combinations of network topology, node capability assignment and routing algorithm. We further presents this

Table 2. Theoretical results of critical injection rate R_c under different combinations, where UC represents uniform capability mode, DC represents degree dependent capability mode, BC represents betweenness dependent capability mode, EBC represents effective betweenness dependent capability mode, SPR represents shortest path routing and EFR represents efficient routing.

(node capability, routing algorithm)	BA	HOT	ER	WS	Lattice	Ring
(UC, SPR)	8.7	16.7	173.7	132.8	280	32
(UC, EFR)	155.3	17.7	325.8	186.8	280	32
(DC, SPR)	312.9	28.5	414.8	194.8	280	32
(DC, EFR)	238.5	29.3	448.2	213	280	32
(BC, SPR)	975.7	702.0	790.9	591.5	280	32
(BC, EFR)	139.6	197.6	347.7	340.1	280	32
(EBC, EFR)	545.8	540.1	656.9	509.5	280	32

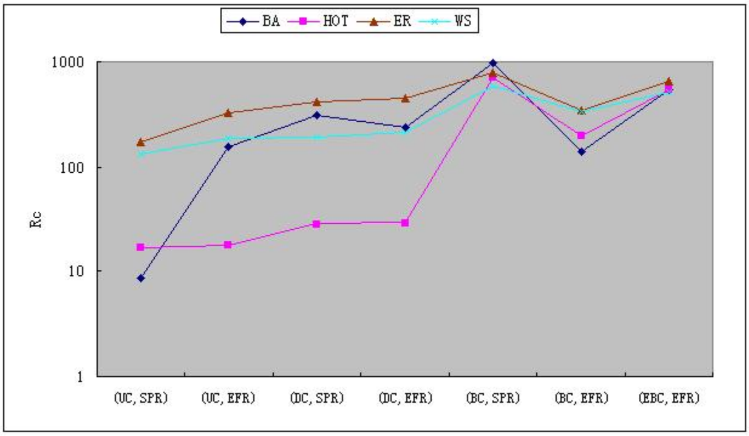

Fig. 2. R_c under different combinations

result in Fig 2 to ease understanding(we eliminate the lattice and ring because they are homogenous networks and thus all combinations have the same effect). From this figure, we find that (a)all networks achieve the highest R_c values when shortest path routing and betweenness based node capability assignment is applied;(b)BA network is sensitive to routing algorithms while HOT network doesn't, the only way to improve HOT network's R_c value is to upgrade key nodes with high betweenness centrality values.

5.5 Designing Cost–C_{max}

Table 3 presents C_{max} values required under different node capability assignment strategies. We also presented C_{max} as the result of different combination strategies in Fig 3. Comparing it with Fig 2, we find that although betweenness based capability assignment enables large R_c values, it also demands the largest C_{max} values, in other words, the largest designing cost. Especially for BA networks, C_{max} spans the widest range. However, BA network also shows good tradeoff property in achieving high R_c and low C_{max}. With efficient routing and effective betweenness based capability model (EBC,EFR), the R_c value is slightly over

Table 3. C_{max} under different combinations of network topology, routing algorithm and node capability mode, where the meaning of short notations are the same as Table 2

(node capability model, routing algorithm)	BA	HOT	ER	WS	Lattice	Ring
(UC, *)	4	4	4	4	4	4
(DC, *)	144.0	160.0	12.0	7.0	4	4
(BC, *)	449.0	169.6	19.5	18.8	4	4
(EBC, EFR)	14.1	122.22	8.1	10.9	4	4

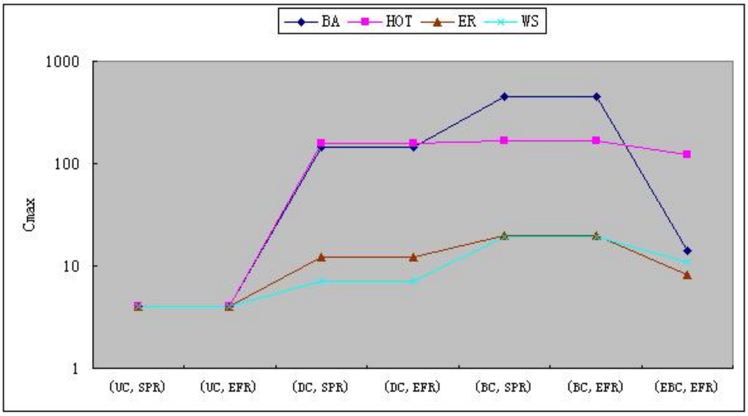

Fig. 3. C_{max} under different combinations

half of the largest R_c value(545.8 vs 975.7), but the C_{max} reduces to less than $\frac{1}{30}$ of the largest C_{max}(14.1 vs 449.0).

5.6 Designing Efficiency

To give a quantitative impression on the efficiency of different network designing strategies, we set $\alpha = \frac{1}{2}$ and presents the DEI indexes for different combinations in Table 4 and further illustrate in Fig 4. In fact, DEI is an indication of whether it can achieve good tradeoff between the two designing objectives, or in other words, whether a cost-effective design exists. We find that BA network shows good property in achieving good tradeoff while HOT network doesn't. On the other hand, for $\alpha = \frac{1}{2}$, we find that the ER random network has the best designing efficiency. Taking all aspects into account, the most efficient designing for $\alpha = \frac{1}{2}$ is the ER network with efficient routing and effective betweenness based node capability model.

Table 4. Network DEI($\alpha = \frac{1}{2}$) for different network designing strategies

(node capability, routing algorithm)	BA	HOT	ER	WS	Lattice	Ring
(UC, SPR)	4.4	8.4	86.9	66.4	140	16
(UC, EFR)	77.6	8.8	162.9	93.4	140	16
(DC, SPR)	26.1	2.2	119.7	73.6	140	16
(DC, EFR)	19.9	2.3	129.4	80.5	140	16
(BC, SPR)	46.0	53.9	179.1	136.5	140	16
(BC, EFR)	6.6	15.2	78.7	78.5	140	16
(EBC, EFR)	145.6	48.9	231.2	154.3	140	16

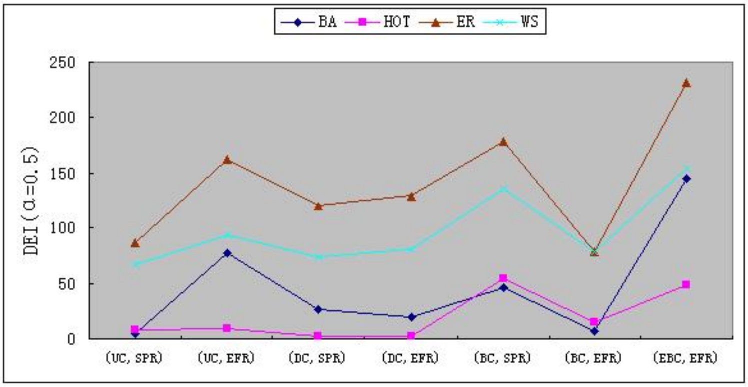

Fig. 4. $DEI(\alpha = \frac{1}{2})$ under different combinations

6 Conclusion

In this paper, we proposed that network designing is a multi-objective designing process and involves several seemingly independent but in fact closely related aspects. We provided a comprehensive view on how to compare different network designing schemes and proposed a quantitative metric, the designing efficiency index, to measure a particular network designing scheme's efficiency. We found that betweenness based capability model combined with shortest path routing can achieve highest network transmission capability, but this scheme also requires the highest cost. By adopting efficient routing and effective betweenness based capability model, BA network can achieve good tradeoff between the two designing goals, thus can be said to have cost-effective designing, while more realistic HOT network doesn't show this property. Taking into account all designing aspects, we found that ER network with efficient routing and effective betweenness based capability model is a good designing choice, possibly the most cost-effective designing among all the designing schemes studied. This may be an interesting finding that shows sometimes random designing is the best.

Regarding these findings, the possible practical significance in reality is listed as follows. First, the difference of traffic dynamics between the networks offers insightful understanding for different network topologies, especially for BA and HOT. Second, these findings provide guidelines for how to upgrade the nodes in a network. We suggest that upgrading should be performed by not only considering a node's structural position in the network, but also the routing algorithm applied. Finally, our findings can help the designing of totally new networks. We pointed out the possible tradeoff between network topology, the routing algorithm applied, the network transmission efficiency achieved and the budgeted payout.

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