Robust Energy-Aware Routing with Uncertain Traffic Demands

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***Abstract*—Energy conservation has become a major challenge to the Internet. In existing approaches, a part of line cards are switched into sleep mode for energy conservation, and the routing is configured carefully to balance energy saving and traffic engineering goals, such as the maximum link utilization ratio (MLUR). Typically, traffic demands are used as inputs, and routing is computed accordingly. However, accurate traffic matrices are difficult to obtain and are changing frequently. This makes the approaches difficult to implement. Further, the routing may shift frequently, and is not robust to sudden traffic changes.**

In this paper, we propose a different approach that finds one energy-aware routing robust to a set of traffic matrices, in particular, to arbitrary traffic demands. Such a routing without energy consideration is known as the demand-oblivious routing, and is well studied. However, the problem becomes much more challenging when energy conservation is involved. To overcome the challenges, we first define a new metric, namely oblivious performance ratio with energy constraint, which reflects the MLUR distance from a routing to the optimal routing when certain energy conservation requirement is satisfied. We model the problem of minimizing the performance ratio, and analyze the lower and the upper bounds. Then, we propose Robust Energy-Aware Routing (REAR) to solve the problem in two phases. REAR select sleeping links based on extended robust link utilization, and compute the routing based on a classical demand-oblivious routing algorithm. We evaluate our algorithms on real and synthetic topologies. The simulation results show that REAR can save XX% of line card power while the performance ratio is less than XX.

I. Introduction

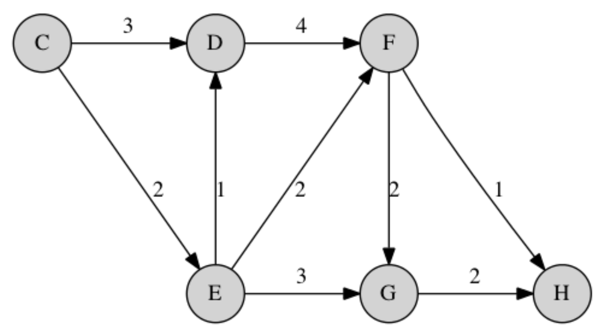
We aim to find the “robust” route for all possible traffic matrix, not only consider performance but also energy consumption in network.

II. Motivation

Suppose two hosts named host A and host B, and there are three links between them, respectively, capacity with 2M, 3M and 5M. Now demands come, with 1M from A to B. we regard the capacity as the power of the link, and the minimum maximum utilization of network links as a metric of the network performance. There are two directions for operating this example. One consider the min power consumption except for the utilization, it is obviously that we should close the larger power consuming links, such as the 5M and 3M links, and all the traffic go through the 2M link. In this way, the min max utilization of network is 0.5 and the power consuming is 2 units (means the power difference come from the link mainly). The other consider the power except for the utilization reversely, so we should split the 1M traffic to three parts, 0.2M across 2M link, 0.3M across 3M link and 0.5M across 5M, consequently with a min max utilization of 0.1, but the power is 10 units however.

Two directions mentioned above both are extremely single-consideration. Previous researchers solve the problem more considerable, include “GreenTE” and “a%-green is engouh”. The former set a threshold of min max utilization, close links as many as possible to achive the most power saving. And the latter one set a destination of the power saving, calculate optimal route for get the min max utilization. Two work have their restriction, which both need a specific traffic matrix that as base of their optimization.

But the need of precise current traffic matrix shound be carefully checked. Although some researcher contribute to this area, the real precise traffic matrix still be a challenge. Take a step back, the dynamic of traffic matrix is more diffcult even if we obtain the precise current one. Futhermore, ISP will not want to change their route policy frequently, as it will result in other route failure possiblly. So our question is that : Is there exist a route both satisfy power and utilization requirement for any traffic matrix given?



David Applegate propose a method for obtain a route wihich is “robust” to variations in demands for a specific network topology.

III. Model

We model the network as a undirected graph $G = (V, E)$, where V is the set of vertices (i.e., routers and end hosts), and E is the set of links (either link between routers or router and end-host). In graph G, two vertices u and v are called connected if G contains a path between u and v. Then We say graph G is connected, if and only if arbitrary pair of vertices in the graph is connected.

Let $\theta(G) = \{(V, E - \{e\}) | e \in E\}$ denote the network set after closing/removing the link e from G. Then, choosing the connected graph from $\theta(G)$ to consist a new set, denoted by $\Theta(G) = \{G | G \in \theta(G)\ \&\&\ G\ is\ connected\}$. We call $\Theta(G)$ as successor of G.

A $traffic\ matrix$ (abbreviation as TM below) is the set of traffic between each Origin-Destination(OD) pair in network G, and a $routing$ specifies how traffic of each OD pair is routed across the network. Usually, there are multiple paths for each OD pair and each path routes a fraction of the traffic. Let m denote the $traffic\ matrix$, which can be represented by a set of trinary group like $(a, b, d_{ab}$, where a and b is the origin and destination of pair respectively, d_{ab} is the traffic demand of the OD pair.

Let r denote the $routing$ mentioned above, which is specified by a set of values $f_{ab}(i, j)$ that specifies the fraction of demand from a to b that is routed on the link (i, j). So an OD pair contribute to the traffic of link (i, j) is $d_{ab} f_{ab}(i, j)$, and all the traffic across link (i, j) can be calculated as :

$$\sum_{(a,b,d_{ab} \in m)} d_{ab} f_{ab}(i, j) \tag{1}$$

Futhermore, we define the utilization of link as traffic acorss the link divide capacity of the link, as ;

$$u_{ij} = \frac{\sum_{a,b} d_{ab} f_{ab}(i, j)}{cap_{ij}} \tag{2}$$

where cap_{ij} is the capacity of the link (i, j).

A common metric for the performance of a given routing with respect to a certain TM is the $maximum\ link\ utilization$. This is the maximum utilization of link over all ones, Formally, the maximum link utilization of a routing r on TM m in network $G(V, E)$ is

$$U_{r,m,G} = \max_{(i,j) \in E} u_{ij} \tag{3}$$

The $optimal\ routing$ in all the possible route R for network G is a routing which minimize the maximum utilization, the minimum maximum utilization is called optimal utilization, can be represented by :

$$OptU_{m,G} = \min_{r \in R} U_{r,m,G} \tag{4}$$

The $performance\ ratio$ of a given routing r on a given TM m and a given network G meaures how far from being optimal, it is defined as the maximum link utilization divided by optimal utilization on the m and G, as following :

$$P(\{r\}, \{m\}, G) = \frac{U_{r,m,G}}{OptU_{m,G}} \tag{5}$$

We now extend the definition of performance ratio of a routing to be with respect to a set of TMs M.

$$P(\{r\}, M, G) = \max_{m \in M} P(\{r\}, \{m\}, G) \tag{6}$$

Obviously, the optimal routing in routing set R for the set of TMs is a routing which minimize the extended performance ratio, such as :

$$P(R, M, G) = \min_{r \in R} P(\{r\}, M, G) \tag{7}$$

I.E. the routing r which arrive at the value of $P(R, M, G)$ is the most "robust" routing for the TM set M in the network G, and if the M range enough, we say that the "robust" routing is independent of specific TM.

But definition of "robust" above will not work well for next situation. Let us take a cycle network topology C as an simple example, in which we should choose one link to close. Before link cutting, the $P(R, M, C)$ is approximate to 2, but no matter which link is chosen to close, the cycle network will change to a line network L. Obviously, the $P(R, M, L)$ will always equal to 1. It means that there is no difference from removing which link, But the contradiction here is that, the choice for which link should be removed is really different because the links are not always the same with each other, such as their capacity.

The reason for the "fake robust" is that, the routing in the successor graph (i.e. L in above example) become unique, the current routing always be the optimal routing. More generally, we should make a little modification for the $performance\ ratio$ as the network self changes.

Let G be the origin network, and the $G^* \in \Theta(G)$ be the successor network from G after closing/removing some link, we define $performance\ ratio\ between\ different\ graphs$ as the performance ratio of successor graph divide the optimal performance ratio of father graph, like :

$$P(R^*, \{m\}, G, G^*) = \min_{r \in R^*} \frac{U_{r,m,G^*}}{OptU_{m,G}} \tag{8}$$

where R^* is the routing set on network G^*.

And question is that how to meaure a successor network topology is "robust" enough for the TM set M when pruning is proceeding. We consider the worst situation, namely the successor network topology has its maximum performance ratio when the TM is $m \in M$, described as following :

$$P(R^*, M, G, G^*) = \max_{m \in M} P(R^*, \{m\}, G, G^*) \tag{9}$$

Now we can say that, if a successor network arrive the minimum performance ratio, it is the "robust" successor network graph. Formally, we define the performance ratio as $optimal\ successor\ performance\ ratio$:

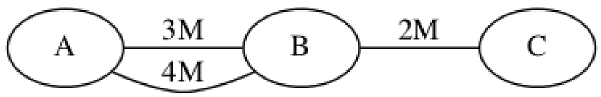
$$P^*(M, G) = \min_{G^* \in \Theta(G)} P(R^*, M, G, G^*) \tag{10}$$

where M is the TM set, and R^* is routing set.

If the scope of M is large engouh, the optimal successor network graph is alwo independent from specific TM.

A. Model Example

We will take an example to explain how to choose the link to close in our experiment. Three hostes include : A, B, C, Three links are with repectively capacity of 3M, 4M and 2M. For simpleness, we suppose there are two TM : $(A, B, 2M), (A, C, 1M), (A, B, 1M), (A, C, 1M)$.For each traffic matrix, the optimal route is obvious, we will trace 2M from A to B across the lower link and trace the 1M from A to C across the upper one for the first traffic matrix, whose maximum link utilization is 0.5. we will trace all the traffic acorss the lower link for the second traffic matrix, whose maximum link utilization is 0.5 as well.



Now for some reason, we will choose one link to shut down for power saving without lose connection of the network. There are two choice, remove either the upper link or the lower link. Let us take a little calculation: when remove the upper one, we should change all the traffic acorss the lower link, as a result, in the first TM the maximum link utilization is 0.75 and the second is 0.5; when close the lower link, we should trace all the traffic acorss the upper link, in the first TM the link utilization is 1 and the other is 0.667. So according to our theory, the $P^*(M,G)$ should be 1.5 and the optimal successor network topology will be the one which 3M link is closed.

IV. Algorithm

In our paper, Robust Energy-Aware Routing (REAR) algorithm works in two phases. Firstly, REAR select links should be sleeping from the origin topology based on extended algebraic connectivity, then compute the robust routing by demand-oblivious routing algorithm.

A. Extend Algebraic Connectivity

Network topology is represented by $G = (V, E)$ as mentioned in Model section, where V is the set of vertices and E is the set of links. We say $A(G)$ is the Adjacency Matrix of graph G, that include information for which vertices of the graph are adjacent to which other vertices. $A(G)$ is a $N \times N$ matrix, where $N = |V|$ and non-diagonal entry a_{ij} equal to the number of edges from vertex i to vertex j, in this paper, a_{ij} always be 1 if $(i,j) \in E$ otherwise 0. And we stipulate the diagonal element a_{ii} be 0.

We say $D(G)$ is the Degree Matrix of graph G, which is a diagonal matrix and diagonal entry d_{ii} denote the degree of node i. It is obvious that there is $d_{ii} == \sum_j a_{ij}$.

Then we define Laplacian Matrix $L(G)$ of graph G as the difference between Degree Matrix and Adjacency Matrix :

$$L(G) = D(G) - A(G) \tag{11}$$

where $D(G)$ is the Degree Matrix and $A(G)$ is the Adjacency Matrix.

In the mathematical field of graph theory, the number of eigenvalues equal to 0 is the number of connected componements of G, so the smallest eigenvalue always be 0. And we call the second smallest one as algebraic connectivity, which is greater than 0 if and only if graph G is connected. Further more, it measures the connectivity and stability of graph, the greater of which, the more connective of graph; and it is a metric of average distance between any two vertices of graph G.

As far as we know, algebraic connectivity regard every link the same, without considering the capacity of each one, but it is ridiculous in network. It is easy to see, link with greater capacity is more important than the same one with lower capacity. and in graph theory, algebraic connectivity value monotonically increased when we increase the weight of link between vertices. So we extend the algebraic connectivity definition by following ways:

1) We change the Adjacency Matrix from binary-matrix to float-matrix, i.e. if $(i,j) \in E$ we set the a_{ij} with the capacity of link l_{ij} instead of binary value 1.
2) Degree Matrix is not ever the denotation for the degree of nodes, but the conbined capacity of all the links adjacent to the node, there is still exist the equation: $d_{ij} == \sum_j a_{ij}$
3) No modification for definition of Laplacian Matrix

We calculate new extend algebraic connectivity from the new Laplacian matrix, denoted by $\lambda_2(G)$.

Topology always have different extend algebraic connectivity values, it is clear that when one link is added or removed from the graph, the extend algebraic connectivity value changes accordingly. And we say the changed value is the impact of this link on the graph. Supposed we sleep link l from graph G, new graph is described as G^*, we defined the impact of link l as :

$$\Delta_l = \lambda_2(G) - \lambda_2(G^*) \tag{12}$$

where $\lambda_2(G)$ and $\lambda_2(G^*)$ is extend algebraic connectivity of G and G^* respectly.

Clearly, Δ_l is always greater than 0, because graph will always lose connectivity when link is removed. Further more, some link will play a more important role in the connectivity of graph, such as the backbone link of network topology. And we say a link l affect more if Δ_l is greater.

B. Algorithm Phase One

REAR sleep as many links as possible without losing much connectivity of graph. Originly, we should calculate impact of all the links and sleep the lowest one from the graph, then repeat calculate and remove process until arrive some specific threhold. Obviously, it is NP-Hard, following is a heuristic algorithm.

For the origin graph, we calculate the impact of every link as Δ_{l_i} , and then sort these values from small to big, output ordered list denoted as Γ:

$$\Gamma = \{..., l_i, ..., l_j, ...\} \tag{13}$$

where $\Delta_{l_i} < \Delta_{l_j}$.

Pay attention we only compute the link impact once at the begining of algorihtm, and the ordered list Γ show the order of 'importantance' among links in the connectivity of the graph.

Now we begin selecting which links should be sleep. We denote the set of the sleeping links as S, and the output of this phase is final graph $G^* = (V, E - S)$. We set $S = \emptyset$, and repeat our selecting process, each iteration we select one link and put it into S. In iteration i, algorithm scan links as the order of Γ and choose one which is still not in the S, we try to remove this link from the graph, if some metric of the current graph do not arrive the threhold we put the link into S then go next iteration, or choose the next link from the Γ for trying to remove otherwise. Algorithm stop until all the links in Γ is tried but there is no one to satisfy the threhold.

So before going ahead our algorithm, there is another thing we should done, what is the threhold for the graph. It does matter for what we concern most of the graph, in our graph, we choose the power consumption. We simple take an power model from 'Green TE' showed in Table xx, and defined the difference of power consumption between two graphs as:

$$diff_p = \rho(G^o_{S,l})/\rho(G^o) * 100 \tag{14}$$

where $\rho(G^o_{S,l})$ is the power consumption of the final graph, when the links set S and link l are both removed from the origin graph G^o, and the $\rho(G^o)$ is the power consumption of the origin graph.

If we set $diff_c$ valued 90%, it means that whenever we try to remove the link l from the origin graph in iteration, the power consumption should never lower than the 90% of origin one. In another words, the output of this phase protect as much connectivity as possible. Following is our implementation:

Algorithm REAR : Phase One

Input: $G(V, E)$, $threhold$;
Output: S in which links should be switched off;
    $G(V, E - S)$ which is the final network topology;
for each link l in E
    $G^* \leftarrow G(V, E - \{l\})$;
    $\Gamma[l] \leftarrow \Delta_l \leftarrow \lambda_2(G) - \lambda_2(G^*)$;
Resort Γ in increasing order based on Δ_l;
$S \leftarrow \emptyset$, $goon \leftarrow true$;
while $goon$
    $goon \leftarrow false$;
    for each link l in $\Gamma - S$
        if $G_{S,l}$ is connected and $\rho(G_{S,l})/\rho(G) < threhold$
            $S \leftarrow S \cup \{l\}$;
            $goon \leftarrow true$;
            break;
return $S, G(V, E - S)$;

C. Algorihtm Phase Two

Once we get the output network topology from the first phase based on extend algebraic connectivity, it is time to compute the robust routing. We first calculate the demand-oblivious rouintg from the origin topology based on algorithm proposed by David Applegate[1]; and adjust routing in details according to the links we switched off in the final topology.

The demand-oblivious routing can be computed by a single LP with $O(mn^2)$ variables and $O(nm^2)$ constraints :

where the $cap(l)$ is the capacity of link l; and $\pi(l, m)$ is the weights for every pair of links l, m; and the variables $p_l(i, j)$ for each link l and OD pair i, j is the length of the shortest path from i to j according to the link weights $\pi(l, m)$.

The routing we get indicate how to arrive at destination node from source node for every OD pair in the origin topology. What is different is that, the flow can be splited in the routing,

min r
$f_{ij}(e)$ is a routing
$\forall$ links l: $\sum_m cap(m)t(l, m) \le r$
$\forall$ links l, $\forall$ pairs $i \to j$:
    $f_{ij}(l)/cap(l) \le p_l(i, j)$
$\forall$ links l, $\forall$ nodes i, $\forall$ edges $e = j \to k$:
    $\pi(l, link - of(e)) + p_l(i, j) - p_l(i, k) \ge 0$
$\forall$ links l, m: $\pi(l, m) \ge 0$
$\forall$ links l, $\forall$ nodes i: $p_l(i, i) = 0$
$\forall$ links l, $\forall$ nodes i, j: $p_l(i, j) \ge 0$

i.e. there may be two paths ($path_1$, $path_2$) both from source node s to destination node d, and the optimal obilious routing trace 70% traffic on $path_1$ and left on $path_2$. However splitting flow is hard handled, we take a transformation for this case like this: when an flow is coming, there is 70% probability we trace it on $path_1$, otherwise $path_2$.

Because all the routing is based on the origin topology, when switch-off links is done, we must adjust the routing as well. Take pair (s, d) for example, the path in routing maybe like $s \to i \to j \to d$, unfortunately link $i \to j$ is switched off in Phase One of Algorithm. For the final topology is still connected, we must can find another path from i to j, such as $i \to k \to j$, then we just replace the routhing $s \to i \to j \to d$ with $s \to i \to k \to j \to d$. Find the path between two nodes of switch-off link is easy by Dijkstra Algorithm on the final topology.

And this is our implementation:

Algorithm REAR : Phase Two

Input: $G(V, E)$ which is the origin topology;
    S which is the switch-off links set generated by Phase One;
Output: $Rouing$ Robust Energy-Aware Routing on new topology
$G^* \leftarrow G(V, E - S)$;
$Replace \leftarrow \emptyset$;
for each link l in S
    $ls \leftarrow$ node of l;
    $ld \leftarrow$ the other node of l;
    $Replace[ls, ld] \leftarrow$ find path from ls to ld on G^*;
$Routing \leftarrow$ run LP on G by CPLEX, fetch routing through parsing result;
for each r in $Routing$
    if $l \in S$ in r
        $s \leftarrow$ source of r;
        $d \leftarrow$ destination of r;
        $r \leftarrow r[s, ls] + Replace[ls, ld] + r[ld, d]$;
return Routing;

V. Samples

For showing obilious performance ratio with energy constraint really make a difference in the switching off link process, we will explain it in two simple topologies, cliques and cycles. On the other hand, we also say that there will be an upper bound for obilious performance ratio with energy constraint, and get the bound according to the topology.

Cycles topology connect all the nodes by a cycle, any node in which has two links joined. Figure 1 show the six nodes cycles topology, let nodes named from A to F and links named by its two vertices, such as l_{ab}. Without loss of generality,

VI. Conclusion

The conclusion goes here.

References

[1] H. Kopka and P. W. Daly, *A Guide to LaTeX*, 3rd ed. Harlow, England: Addison-Wesley, 1999.