Power-Aware Routing in Networks with Delay and Link Utilization Constraints

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***Abstract*—This paper addresses the NP-hard problem of switching off bundled links whilst retaining the QoS provided to existing applications. We propose a fast heuristic, called Multiple Paths by Shortest Path First (MSPF), and evaluated its performance against two state-of-the-art techniques: GreenTE, and FGH. MSPF improves the energy saving on average by 5% as compared to GreenTE with only 1% CPU time. While yielding equivalent energy savings, MSPF requires only 0.35% of the running time of FGH. Finally, for Maximum Link Utilization (MLU) below 50% and delay no longer than the network diameter, MSPF reduces the power usage of the GÉANT topology by up to 91%.**

Keywords - power savings; routing; multiple paths; maximum link utilization; bundled links; shortest path

I. INTRODUCTION

Current backbone networks are over-provisioned to accommodate traffic bursts, and route/link failures. However, they consume unnecessary amount of energy during off-peak periods since the power consumption of routers and their line cards is independent of link load [3]. To this end, Chiaraviglio *et al.* [4] proposed a solution to the problem of finding the minimum set of routers and links that can accommodate a given traffic demand. However, their solution does not consider the effects of traffic delays and maximum link utilization *after* these routers are switched off, which may reduce a network's fault tolerance capability. Vassos *et al.* [15] studied the impact of power in interconnection networks, and explored the design space for shutting down links. However, they did not consider the impact of delay and link utilization on network performance. Other works such as Zhang *et al.* [5] proposed a traffic engineering technique, called GreenTE, to reduce energy expenditure by turning off unused links while considering maximum link utilization (MLU) and delay constraints. This optimization problem is known to be NP-complete. GreenTE is effective in selecting unused links, but its computation is slow for large networks. Fisher *et al.* [6] observed that each network link may comprise of two to twenty cables [14]. They then propose three algorithms, e.g., FGH, to turn-off unused cables. While FGH is effective in reducing energy, it does not guarantee both MLU and delay constraints. Further, like GreenTE [5], its running time is prohibitive on large networks.

Our contributions in this paper are twofold. First, we propose an optimization problem to maximally turn-off unnecessary cables in a network with bundled links while meeting two performance constraints: MLU and traffic delay. Each link e_{ij} comprises of $w_{ij}\geq 1$ cables that can be turned off independently and the delay can be either the network's diameter or λ times the delay of its original shortest path, for a given delay multiplier $1.0\leq\lambda\leq 2.0$. The NP-complete problem generalizes those in [5] and [6]; *i.e.*, for $w_{ij}=1$ and $\lambda=2.0$, it reduces to that in [5], and it becomes that in [6] if we ignore the two constraints. Second, we design a heuristic, called Multiple Paths by Shortest Path First (MSPF) that solves the problem more efficiently and as effective, if not more, than the solutions in [5] and [6]. MSPF runs on average 99% faster than GreenTE [5] while improving its energy savings by 5%. Further, MSPF uses only 0.35% of the running time of FGH [6], while yielding equivalent energy savings.

II. PROBLEM FORMULATION

A. Network Model

Consider a network modeled by a directed graph $G(V, E)$, where $V(E)$ is the set of n nodes (m links). Each node represents a router and each link e_{ij} between nodes v_i and v_j represents a bundled link as a communication channel with capacity $c_{ij}>0$. Each link e_{ij} consists of $w_{ij}\geq 1$ cables, *i.e.*, each link e_{ij} corresponds to w_{ij} copies of cable b_{ij}. Our model generalizes that of [5] which assumes equal bundle size w_{ij}. Each b_{ij} that can be turned-off independently has the same bandwidth and consumes the same energy p_{ij}. Let $n_{ij}\leq w_{ij}$ be an integer that represents the total number of powered-on cables in e_{ij}. Let $D=\{D_\alpha=(s, t, f^\alpha)$ | a demand D_α from a source node $s=1,\ldots,n$ to a terminal node $t=1,\ldots, n$ that has traffic flow f^α $\}$, and $CP_\alpha=\{cp_{\alpha,q}$ | a candidate path $q=1, 2, \ldots, |CP_\alpha|$ that can be used to route demand D_α with delay no more than $d_{T,\alpha}$ $\}$. The variable $\delta_{ij}^{\alpha,q}$ has a value of 1if the q^{th} candidate path for D_α contains link $e_{ij}\in E$, and it is 0 otherwise. Let d_α be the length of the shortest path. When a traffic demand is routed through multiple (s,t) paths, we set its traffic delay to the maximum hop count among the paths. We denote f_{ij}^{st} or f_{ij}^{α} as the flow on link

e_{ij} of demand D_α, and f_{ij} the total flow on e_{ij}. Lastly, the remaining/spare capacity on link e_{ij} is $r_{ij} = c_{ij} - f_{ij}$.

B. Problem Statement

Given a network $G(V, E)$ and a traffic demand set D, the problem is to generate (i) the minimum number of powered on cables, and (ii) the path set MP_α that can be used to route each traffic in D_α while using only the powered-on cables, subject to two constraints: (C1) the utilization of each link e_{ij} is no larger than a given threshold u_T, *i.e.*, $u_{ij} \le u_T$, and (C2) the length of each path $cp_{\alpha q} \in CP_\alpha$ is no longer than a given constraint $d_{T,\alpha}$. In other words, the problem is to find as many cables as possible that can be switched off while satisfying all traffic demands in D under constraints (C1) and (C2). Similar to [5], we set the MLU to $u_T \le 50\%$; this over-provisioning is necessary to maintain network fault tolerance and performance. For delay, we consider two path length constraints when routing each demand D_α with powered-off cables: (C2.1) each D_α is routed through one or more paths with a bounded delay $d_{T,\alpha} \le$ ND; ND is the network diameter of the original network, or (C2.2) each D_α is routed through one of more paths with threshold delay $d_{T,\alpha} \le d_\alpha * \lambda$, for a multiplier $1.0 \le \lambda \le 2.0$. Formally, we have,

$$\text{Min} \quad \sum_{e_{ij} \in E} p_{ij} n_{ij} \tag{1}$$

$$\text{s.t.} \quad \sum_{j \in V} f_{sj}^{\alpha} = \sum_{j \in V} f_{jt}^{\alpha} = f^{\alpha}, \forall D_\alpha \in D \tag{2}$$

$$\sum_{j \in V} f_{ij}^{\alpha} = \sum_{j \in V} f_{ji}^{\alpha}, \forall D_\alpha \in D, i \neq s, t \tag{3}$$

$$\sum_{D} \sum_{CP_\alpha} \delta_{ij}^{\alpha,q} f_{ij}^{\alpha} \le (n_{ij} / w_{ij}) * c_{ij}, \forall e_{ij} \in E \tag{4}$$

$$(w_{ij} * \sum_{D} f_{ij}^{\alpha}) / (n_{ij} * c_{ij}) \le u_T, \forall e_{ij} \in E \tag{5}$$

$$| cp_{\alpha,q} | \le d_{T,\alpha} = d_\alpha * \lambda, \forall D_\alpha \in D \tag{6}$$

Eq. (1) quantifies the total energy consumed by all active cables. Eq. (2) ensures that the sum of flows leaving a source or entering a destination equal to f^{α}. Eq. (3) ensures that no flow is lost, while Eq. (4) computes the flow in each link and restricts each link to carry flow no more than its capacity. Eq. (5) computes the link utilization and limits it to at most u_T. Finally, Eq. (6) restricts each path delay to be no more than $d_{T,\alpha}$. The resulting formulation is a MIP problem, which is NP-hard, due to the integer variables n_{ij}.

III. GREEN ROUTING ALGORITHMS

Fig. 1 describes the main steps of MSPF. Step 1 uses Yen's algorithm [8] to generate k shortest paths, CP_α, for each demand D_α, each of which has delay no more than $d_{T,\alpha}$. Since we set each link's weight to one, the shortest path in the k paths has the smallest hop count; the next shortest has the second smallest, and so forth. Step 2 uses the function ***D-Flow*()** to distribute the traffic flow of each demand D_α through one or more candidate paths in CP_α. The function aims to distribute the flow starting from the shortest candidate path $cp_{\alpha 1}$. If $cp_{\alpha 1}$ cannot satisfy all flow of D_α, it uses the second candidate path $cp_{\alpha 2}$ to carry the remaining flow, and so forth, until the flow of each demand D_α is supported by the network. The function returns false if the flow in D_α cannot be routed through the candidate paths. Otherwise, it returns true and creates a set of MP_α that contains all paths used to route demand D_α. Notice that in Step 2 the function would always return true since we assume that the original network has sufficient capacity to meet the demand requirements. Step 3 calculates the total flow f_{ij} for each link e_{ij}, and computes the remaining link capacity $r_{ij} = c_{ij} - f_{ij}$ which in turn is used to calculate the maximum number of redundant cables $\lfloor r_{ij} \rfloor$ to shut down.

Step 4a) repeatedly selects a candidate cable b_{ij} to switch off; it targets the cable whose link e_{ij} has the largest remaining capacity r_{ij}, as calculated using (7).

$$r_{ij} = u_T * n_{ij} * c_{ij} / w_{ij} - f_{ij}, \forall e_{ij} \in E \tag{7}$$

Step 4b) uses function ***Reroute-D*()**, shown in Fig. 2, to reroute the flow in one or more paths in MP_α that are affected by the removal of b_{ij}. If rerouting is possible, it deletes b_{ij} and puts it in the set of powered off cables B_d. Otherwise, it knows that the cable must be switched on to ensure the feasibility of satisfying all demand flow; therefore it sets $fix(e_{ij}) = TRUE$. When feasible, the function generates a new set MP_α for each demand D_α affected by the cable's deletion. Steps 4a) and 4b) are repeated until each $fix(e_{ij})$ is *TRUE*.

We define the set $B_d = (b_{ij} \mid$ all powered off cables in $\forall e_{ij} \in E)$. Step 1 of function ***Reroute-D*()** repeatedly finds each D_α affected by the deletion of edge *del_e*; D_α is affected if any path in MP_α contains *del_e*. The step places all paths that contain *del_e* in the set DP_α. Then, for each $e_{ij} \in P$ and each $P \in DP_\alpha$, Step 2 increases u_{ij} by the flow of path P. This step is needed since the function wants to redistribute the flow of each path in DP_α. However, as shown in Step 4, the function will revert to each u_{ij}'s capacity if redistributing the flow in Step 3 is not feasible. In Step 3, the function aims to distribute the affected flow of D_α, *i.e.*, f^{α}-*flow*(DP_α), where *flow*(DP_α) denotes the total flow of all paths in DP_α, through the remaining candidate paths, *i.e.*, (CP_α-DP_α). If function ***D-Flow*()** returns false for any D_α, deleting *del_e* is not feasible, and therefore function ***Reroute-D*()** returns false.

1) For each demand $D_\alpha \in D$, generate CP_α;
2) For each demand $D_\alpha \in D$, Call ***D-Flow***(f^{α},CP_α);
3) For each e_{ij}, calculates r_{ij}, remove the maximum cables such that all flows are still satisfied and set $fix(e_{ij}) \leftarrow FALSE$ for each link e_{ij};
4) **Repeat**
   a) Find a candidate edge $e_{ij} \in E$ using (8), remove b_{ij}, and put the cable in B_d.
   b) Call ***Reroute-D***(e_{ij})
      (i) If feasible go to Step 3.
      (ii) If not feasible, retain b_{ij}, remove it from B_d, and set $fix(e_{ij}) \leftarrow TRUE$,

   Until $fix(e_{ij}) = TRUE$ for every $e_{ij} \in$ E.

Figure 1. MSPF algorithm

For each $D_\alpha \in D$
1) Place all paths in MP_α that contain *del_e* in DP_α
2) Increase u_{ij} of e_{ij} in path $P \in DP_\alpha$ by the flow in P
3) Call ***D-Flow***((f^{α}-*flow*(DP_α), (CP_α - DP_α))
4) If not feasible, retain the original value of each u_{ij} in Step 2 and return false; else return true.

Figure 2. Function Reroute-D(*del_e*)

IV. EVALUATION

A. Experiment Setup

To evaluate MSPF's performance, we used four topologies, *i.e.*, Abilene [10], GÉANT [11], Sprint [7] and AT&T [7]. For each network and each link e_{ij}, we consider bundle size w_{ij} ranging from 1 to 10 and MLU $u_T \leq 50\%$.

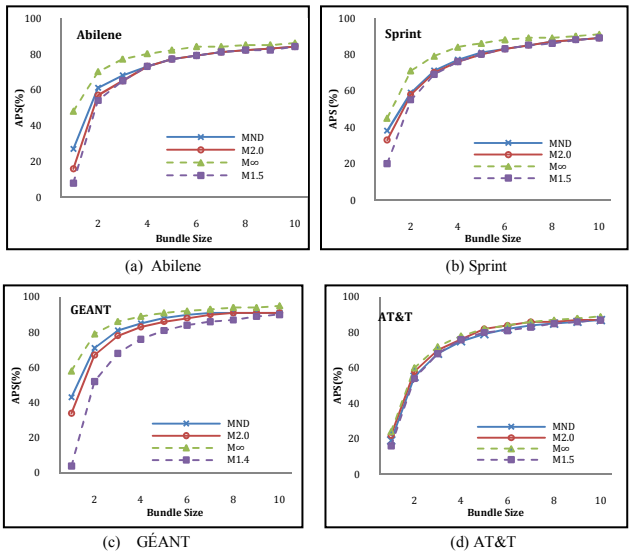
We used the Abilene topology and traffic matrices measured on Sep. 5th, 2004 for every five minutes, which are provided by the authors of [10]. For GÉANT, its traffic matrices were collected on May 5th, 2005 for every 15 minutes; we obtained both the topology and traffic matrices from the authors of [11]. For Sprint and AT&T, we randomly generate a traffic matrix using the gravity model [12], and scaled the traffic to obtain 40 different traffic matrices. Simulation runs were carried out on a Linux PC with 3.07GHz CPU and 8GB RAM. We ran source codes of [5] and [6], provided by their respective authors, using the CPLEX [13] LP solver.

B. Power Savings

We compute the power saving ratio as the total power of sleeping cables over the total power of all cables in the network. The power consumption of line-cards we use in the evaluation is specified in [9]. Let M_{ND} and M_{λ} represent the energy savings generated by MSPF when the delay constraints (C2.1) and (C.2.2) are set to $d_{T,\alpha} \leq$ ND and $d_{T,\alpha} \leq d_{\alpha} * \lambda$, respectively. Further, M_{∞} denotes the upper bound on energy saving when the delay constraint is set to infinity. We used the LP solution in [5] to find the minimum delay multiplier λ that allows a feasible solution for Abilene, GÉANT, Sprint and AT&T, which require a minimum λ of 1.5, 1.4, 1.5 and 1.5 respectively. We used the pre-computed λ in MSPF to produce the lower bound energy saving of the networks. In other words, $M_{1.5}$, $M_{1.4}$, $M_{1.5}$, $M_{1.5}$ are the lower bound energy savings on the respective networks produced by our MSPF.

Fig. 3(a) shows the average power savings for Abilene over the 288 traffic matrices for w_{ij}=1,2, …,10. For w_{ij}=1, M_{ND}=27% is better than $M_{2.0}$=15% because, for each D_{α}, there are more paths with $|cp_{\alpha,q}| \leq$ ND than $|cp_{\alpha,q}| \leq 2.0 * d_{\alpha}$; thus MSPF can use more candidate paths for M_{ND} than for $M_{2.0}$. It also shows that the average power savings increases sharply when the bundle size increases from 1 to 2, and 2 to 3 for both M_{ND} and $M_{2.0}$. Notice that MSPF produces the best energy saving M_{ND}=$M_{2.0}$=84% for w_{ij}=10. For M_{∞} and $M_{1.5}$, they have the same trend as M_{ND} and $M_{2.0}$ when the bundle size increases from 1 to 10. M_{∞} starts from the 46% to 86% while $M_{2.0}$ is from 8% but still to 84%.

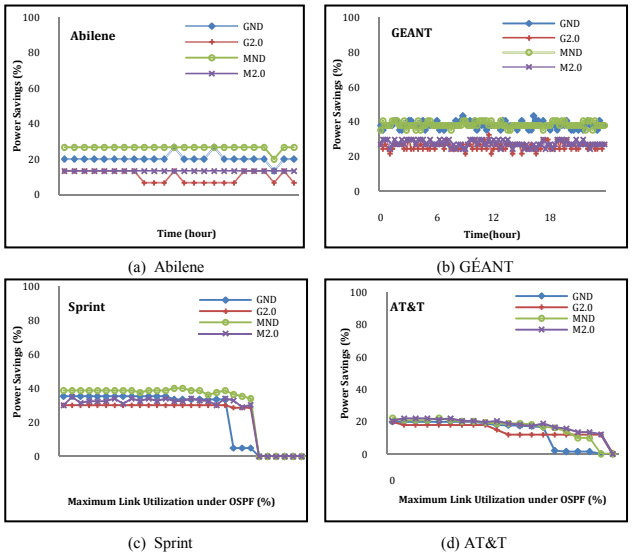
Fig. 3(c) shows the power saving of GÉANT averaged over the 96 traffic matrices for w_{ij}=1, 2, …,10. For w_{ij}=1, $M_{2.0}$=34% is lower than M_{ND}=43% because the network contains fewer paths that has length $|cp_{\alpha q}| \leq 2 * d_{\alpha}$ than $|cp_{\alpha q}| \leq$ ND; thus MSPF has a smaller search space on the former than the latter constraint. Notice the significant jump in energy savings, i.e., M_{ND}=71% and $M_{2.0}$=67%, when the bundle size increases to w_{ij}=2. Both M_{ND} and $M_{2.0}$ reach their peak at 91% when w_{ij}=10. The gap between M_{∞} and $M_{1.5}$ is very large; in fact, it exceeds 50% for w_{ij}=1 but less than 5% for w_{ij}=10.



(a) Abilene (b) Sprint

(c) GÉANT (d) AT&T

Figure 3. Power Savings of MSPF



(a) Abilene (b) GÉANT

(c) Sprint (d) AT&T

Figure 4. Comparison between MSPF and GreenTE[5]

Fig. 3(b) and (d) show the average power savings of Sprint and AT&T for w_{ij}=1 to w_{ij}=10. For Sprint, MSPF uses the first 100 shortest paths to reroute each demand, *i.e.*, k=100; we set k=20 for AT&T. As shown in Fig. 6 and 7, the power savings for Sprint and AT&T also increase sharply as we increase the bundle size from 1 to 2; their peak also occurs when w_{ij}=10. For Sprint, the upper bound M_{∞}=42% is more than twice that of the lower bound $M_{1.5}$=19%. For the AT&T, the upper bound is very close to the lower bound, *i.e.*, M_{∞}=22% versus $M_{1.5}$=19%.

C. MSPF versus FGH

While FGH [6] guarantees that its result would provide sufficient powered on cables for rerouting the given traffic demands, the length/delay of rerouted traffics might exceed their upper bound. Further, the solution may increase the utilization of each link to be above a threshold that may affect

TABLE I. AVERAGE RUNNING TIME (CPU SECONDS); u_T=100% AND λ=∞

Algorithm	Abilene	GÉANT	Sprint	AT&T
MSPF_NC	0.037	1.71	3.526	10.35
FGH	5.1	63.9	1184.3	2965.2

TABLE II. AVERAGE POWER SAVING (%); u_T=100% AND λ=∞

Algorithm	Abilene	GÉANT	Sprint	AT&T
MSPF_NC	53.3	58.1	45.29	23.64
FGH	53.3	58.5	43.02	25.3

the network's resilience against failures or network congestion during peak hours. To compare the performance of MSPF against FGH, we set u_T=100% and λ=∞, *i.e.*, a scenario where there is no upper limit on link utilization nor traffic delay; the results are outlined in Table III and IV. As shown in Table III and IV, MSPF runs significantly faster than FGH while producing similar energy savings. MSPF requires only 0.73%, 2.68%, 0.3%, and 0.35% of the computation time of FGH for the Abilene, GÉANT, Sprint, and AT&T networks respectively. Notice that MSPF produces equivalent or better energy savings for Abilene and Sprint. Further, MSPF is more efficient as compared to FGH on larger networks, *i.e.*, Sprint and AT&T.

D. MSPF versus GreenTE

GreenTE [5] assumes a hierarchical topology, which is typical of a Wide Area Network (WAN) where all links are assumed to be bidirectional. Thus, each pair of directional links from v_i to v_j, *i.e.*, link e_{ij} and e_{ji}, must be turn on or off together. GreenTE aims to maximally switch off paired directional links. Further, their model considers $d_{T,\alpha} \leq$ ND or $d_{T,\alpha} \leq d_\alpha$*2.0, w_{ij}=1; the model does not consider links with bundled cables. To ensure fair comparison, we set the same values for u_T, $d_{T,\alpha}$, and w_{ij} for both GreenTE and MSPF. Let G_{ND} and $G_{2.0}$ represent the energy saving produced by GreenTE when its delay constraint is set to the network diameter and twice of the shortest path, respectively.

Fig. 4(a) and (b) show a comparison of power savings with $u_T \leq$50% on Abilene and GÉANT over 24 hours. As shown in Fig. 4(a), for Abilene, MSPF can shut down more cables than GreenTE, resulting in energy saving of almost M_{ND}=27%, a 7% improvement over GreenTE. For delay constraint C2.2, MSPF consistently obtained $M_{2.0}$=13.33%, better than GreenTE whose $G_{2.0}$ ranges between 8% and 13.33%. In Fig. 8, for GÉANT, the average power savings of running MSPF is always larger than GreenTE with $\lambda = 2.0 (G_{2.0} \leq M_{2.0})$; *i.e.*, around 25%. In terms of running time, MSPF requires only about 2-3 CPU seconds to produce its results, significantly faster than GreenTE, which required 300 CPU seconds while producing results that incur higher energy expenditure.

Fig. 4(c) and (d) compare the performance of MSPF against GreenTE when the MLU under Open Shortest Path First (OSPF) increases from 2 to 100% for Sprint and AT&T, using the traffic matrices generated as described in Section IV.A. As shown in Fig. 9, for $u_T \leq$70%, MSPF outperforms GreenTE, on average about 5% in power saving for delay constraint C2.1; see M_{ND} and G_{ND}. Similarly, MSPF achieves power saving $M_{2.0}$ on average 3% better than $G_{2.0}$ generated by GreenTE. Notice that GreenTE produces the results for these large topologies in 300 seconds; CPLEX [13], used in GreenTE, was unable to produce the optimal solution, and therefore, as suggested in [5], we stopped CPLEX after it ran for 300 seconds. In contrast, MSPF uses approximately 10 seconds while producing better energy savings for Sprint and AT&T's networks.

V. CONCLUSION

We have described a problem to reduce the energy usage of networks comprising links with bundled cables. Our MSPF turns off unused cables during off-peak periods such that the remaining powered on cables have sufficient capacity to support the given traffic demands. Further, each demand is only re-routed through one or more paths with lengths no longer than a given constraint, and each link's utilization does not exceed a given threshold. Our results show that MSPF is superior against two state-of-the-art techniques. We will extend our work so that the resulting network also provides a lower bound on reliability.

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