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RESEARCH ARTICLE

Multi-Stage Power-Aware Intelligent Adaptive Routing Algorithms in Bundled Links Based Backbone Networks

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ABSTRACT The increasing energy consumption in backbone networks has been one of crucial concerns in Information and Communications Technology (ICT) sector. From a viewpoint of intelligent adaption, we propose Green Routing in Backbone networks with Bundled links, which is referred to as GRB2, to investigate the substantial power saving in a bundled link based backbone network for above enormous challenges from severe alarming statistics of the issues on economy, energy and environment. We formulate the above problems as Mixed Integer Linear Programming (MILP) models and develop power-aware greedy heuristics to solve them. We have investigated and compared the different characterizations of the solutions to the proposed problems by evaluating network power consumption including Power Saving Ratio (PSR) profile over time, PSR profile under different Maximum Cable Utilization (MCU) and PSR profile under different Bundled Sizes (BSs) and network performance including Powered-Off Cable Rate (POCR), Mean State Switching Times (MSST) and Mean Running Time (MRT) for various traffic demands during PPs and OPPs under different real backbone network topology scenarios compared with MSPF, SSPF, and HDEER. Experiment results show the different power-saving potential of these solutions once applied in the backbone network.

INDEX TERMS Green networking, power awareness, traffic engineering, low power idle, bundled links.

I. INTRODUCTION

In the last decade, energy efficiency has become a high priority objective in the ICT sectors. The backbone networks constitute an important part of the ICT infrastructure and thus consume a significant amount of energy [1]. The main reason is the fact that the major factors considered by ISPs in the early designs of the backbone networks are availability and user's satisfaction, which results in the overprovisioning of network resources and networking elements maintained at almost the same amount of energy consumption regardless of their utilization [2]. Indeed, the average networking element utilization in backbone networks of large ISPs is very low especially about 30%-40% during the off-peak periods and thus this leads to most of the network resources underutilized [3].

The severe situation will last a while yet until we take some effective measures. Cisco's annual Internet report (2018–2023) estimated that there will be 29.3 billion networked devices by 2023, up from 18.4 billion in 2018, and there will be 5.3 billion total Internet users (66 percent of global population) by 2023, up from 3.9 billion (51 percent

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of global population) in 2018 [4]. It has been reported that power consumption of ICT sectors is responsible for 2%-10% of the global total electricity consumption and this proportion has increased rapidly in recent years with the surging user population and the emergence of more and more new Internet services [5]. The tremendous energy consumption of large-scale networks will become a stumbling block to their further developments unless energy efficiencies can be significantly improved [6]. In a typical ISP/telco network configuration, the core network represents about 30% of the power consumption [7]. While access networks are currently responsible for the most part of the energy consumption, it is envisaged that IP/MPLS core networks and data centers will dominate the growth in the future [8]. In the newest SMARTer2030 report in 2015, GeSI estimated the ICT sector's CO_{2e} (carbon dioxide equivalent) emissions "footprint" was expected to be 1.25Gt in 2030, about 1.97% of global emissions, of which networks' CO_{2e} will be 1.25Gt and account for 24% of total [9]. It is more than likely that energy consumption and carbon emissions will continue to increase in coming years [10].

Accordingly, the Dynamic Power Management (DPM) based Low Power Idle (LPI) policy has been proposed to address the alarming energy waste and serious environmental issues by reducing network power consumption and greenhouse gas emissions. LPI policy was defined and standardized in the IEEE 802.3az standard, which is actually a low energy consumption state that may be enabled during periods of low link utilization in which either side of a link may disable portions of device or system functionality, and when these portions are needed to transfer data later, they will be repowered [11]. Moreover, pairs of routers are typically connected, for each traffic direction, by multiple physical links that form one logical bundled link in modern backbone networks [12], [13]. The technique is called link aggregation, and defined and standardized by IEEE 802.1AX. Link aggregation allows one or more links to be aggregated together to form a Link Aggregation Group (LAG), such that an aggregator client can treat the LAG as if it were a single link [14]. Link aggregation allows a bundle of parallel full-duplex point-to-point links to be used as if they were a single link and also supports the use of multiple links as a resilient load sharing interconnect between multiple nodes in two separately administered networks [14]. Link aggregation can easily upgrade the link capacity by adding new physical links.

Our proposed green routing and network planning consist in configuring and deploying a necessary set of components (line cards or chassis) equipped in each network element (a node or a link) in advance by relying on power-aware routing mechanisms such that the powered-on infrastructures is minimized while satisfying the requirements of robustness and performance. By leveraging a few macro-period reference traffic scenarios characterized by daily traffic profiles according to the day-night discipline, ISPs can plan network resources allocation by identifying reference traffic scenarios through their network management platform, precomputing off-line a set of power-aware routing solutions and determining different powered-on/off infrastructure configurations for each macro-period to save energy costs and potentially reduce equipment footprints in backbone networks. Note that this planning methodology can be also combined with online monitoring tools that can react to unexpected traffic spike situations by restoring sleeping network elements.

Our main contributions can be summarized as follows:

a) We provide a fine-grained port-level optimization formulation to address the problem of optimizing the total power consumption of the bundled link based backbone network under the QoS constraints.
b) Targeting the bundled link based power-saving routing from a perspective of intelligent adaption, we devise Traffic Engineering (TE) based Power-aware Greedy heuristics (TEPG) which is split into two parts of the hop-by-hop Green Greedy Routing stage (GGR) and the Traffic Assignment stage inside the Bundled links (TAB).
c) In order to obtain a minimum network subset with as few powered-on elements as possible, we elaborate GGR by (1) an available capacity of neighbor nodes based hop-by-hop routing stage-ACNN; (2) a greedy pruning stage-GP; (3) a feasible checking stage for routing-FC and (4) a greedy checking stage for pruning-GC.
d) We perform an exquisite pruning and checking for determining each network element to be powered off according to the different criteria in the stages of GP and GC.
e) We distinguish two class of TAB according to the different behavior of cables forming a bundled link and then further divide TEPG into TEPG_U and TEPG_I to solve them accordingly.
f) We conduct comprehensive experiments to evaluate and analyze the power-saving benefits and performance of TEPG in terms of PSR profile over time, PSR profile under different MCU, PSR profile under different BSs, POCR, MSST and MRT over real network topologies under different traffic scales scenarios during different time periods.

The rest of the paper is organized as follows. Section 2 reviews the current related research on the green routing and network planning schemes. Section 3 introduces power profiles of network elements and the problem formulations of GRB2. In Section 4, heuristics are devised to solve the GRB2. Section 5 presents our evaluation methodology, and compares and analyzes a series of experimental results. Finally, conclusions are drawn in Section 6.

II. RELATED WORK

Together with the world-wide concerns to establish a green Internet, more and more routing and network planning schemes have included power-aware consideration into their design principles depending on the different power-saving methodologies. Most of the existing green routing and network planning work falls into the LPI and non-bundled link based energy-saving research, and only a small amount of work is devoted to adopting TE methodology and link aggregation technology.

A first set of work [15], [16], [17], [18] has focused on the study of green routing and network planning by deploying LPI policy. The authors in [15] applied a generic model for router power consumption in a set of target network configurations and used mixed integer optimization techniques to investigate power consumption, performance and robustness in static network design. They used a flexible optimization framework to allocate resources in target networks in a power-aware fashion and used a state-of-the-art branch-and-cut solver-CPLEX to solve the optimization problem. The authors in [16] proposed a novel energy-efficient routing approach called safe and practical energy-efficient detour routing (SPEED) for power savings in IP networks and developed a heuristic in SPEED to maximize pruned links in computing energy-efficient routings. Reference [17] proposed a novel approach to switch off network nodes and links while still guaranteeing full connectivity and maximum link utilization. They provided an integer linear programming formulation of the problem, which shows that it is a NP-complete problem, and proposed some greedy heuristics to solve it. Reference [18] achieved the reduction of power consumption in IP-over-WDM networks by selectively turning off line cards during periods of low traffic, with consideration of the cost incurred when the network is reconfigured. They formulated the power-aware logical topology design with reconfiguration costs as an optimization problem and then presented three heuristics to solve it.

A second set of work [19], [20], [21], [22], [23], [24] has been aimed at achieving green networking by TE. In [19], the authors investigated the relevant and challenging problem of energy-aware IP TE with shortest path routing and proposed a heuristic, namely the Mixed Integer Linear Programming based algorithm for Energy-aware Weights Optimization (MILP-EWO), to minimize the energy consumption in backbone networks. Reference [20] proposed a novel strategy, called Energy Saving IP Routing (ESIR), to save energy in an IP network during low traffic hours, which puts a set of links in low power mode and reroutes the paths crossing them. The authors in [21] proposed a green TE approach named ''hot potato low utilization'' which reroutes traffic from lowly utilized links and aggregates said traffic onto highly utilized links whilst minimizing any changes to the corresponding egress router of a given destination. The authors in [22] studied green TE techniques in backbone networks which aim to establish as many arriving label switched path requests as possible while utilizing the minimum number of links/routers and proposed two novel Border Gateway Protocol (BGP)-aware TE techniques to study the impact of green TE methods on BGP. The authors in [23] proposed a segment routing based TE strategy from the network operation and management point of view, where a demand can be directed through certain segments to achieve an efficient routing approach for deployment in carrier IP backbone networks. In [24], the authors studied demand-oblivious routing which is a promising technology for TE and defined a Green Extended Oblivious Performance Ratio (Green-EOPR) problem, which selects a given number of links to prune and minimizes the EOPR. They also developed efficient pruned link selection heuristics to solve Green-EOPR for such purpose as energy conservation. All the second group of works carried out their research on exploring energy-saving potentials of TE in green networking also based on the non-bundled links model.

Two sets of work mentioned above carried out their research on the green routing and network planning without adopting the link aggregation technique in networks, that is, their energy-saving investigations are all on the basis of non-bundled links. In recent years, the third set of works [25], [26], [27], [28] have been devoted to concern the green routing and network planning problems in the network with the bundled links. In [25], the authors proposed the problem to reach a better tradeoff between energy-saving performance and congestion risk by setting different value combinations of two parameters: the utilization threshold and sublink-adding strategy, and then developed a dynamic and hybrid local heuristic threshold-based algorithm to solve it. Reference [26] proposed a component-level dynamic power-aware energy-saving mechanism over the bundled link based backbone network, in which the incoming traffic size of nodes is firstly dynamically predicted for a short term, then a fine-grained port number conversion algorithm is adopted to determine the number of ports to be regulated, then the corresponding ports convert their power states according to the sleeping and awakening rules and finally a novel hierarchical scheduling algorithm is devised to schedule the packets. Reference [27] proposed a network-level green energy-saving mechanism over the backbone networks, that is, a smallest remaining capacity first based green routing algorithm is used to plan the global routing paths in the networks in a global view, which makes the number of the bundled links powered minimum, and further a green-best fit deceasing algorithm is used to gather traffic loads flowing through a bundled link to the smallest set of physical links in the local view, which enables the physical links powered off as much as possible. To reduce the energy consumption of core networks with bundled cables, the authors in [28] proposed a scheme to deactivate the maximum possible number of cables, and associated equipment, while considering hose-model traffic, and then introduced a mixed integer linear problem formulation that yields the optimal solution and a more practical and near optimal heuristic algorithm for large networks.

Compared with the above work, we investigate the power-aware routing and network planning to achieve green networking from the TE viewpoint jointly with the impacts of different behaviors of the cables forming a bundled link on power saving benefits and performance.

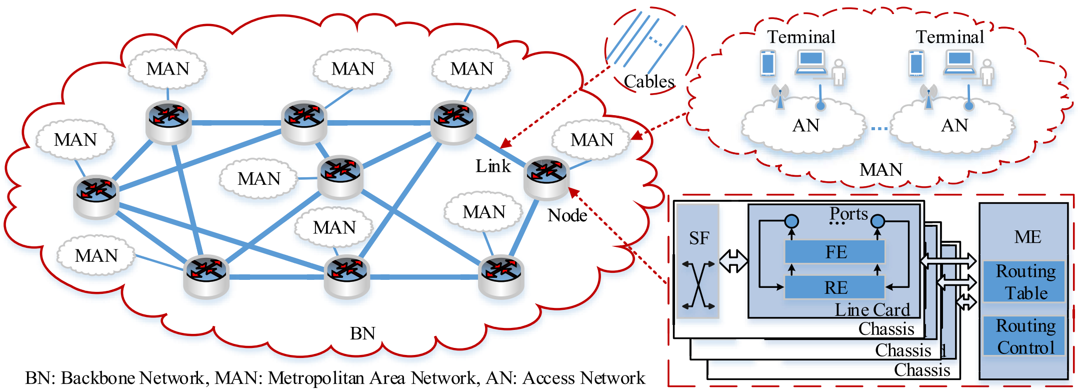

FIGURE 1. Network architecture.

III. PROBLEM FORMULATION

A. POWER PROFILES

Model a network by a directed graph $G = (V, E)$ as shown in Fig. 1, where V is a set of vertices representing nodes and E is a set of edges representing links. Each node $i \in V$ consists of multiple chassis (CHAs), line cards (LCs), a master engine (ME), a switching fabric (SF), multiple forwarding engines (FEs) and multiple replication engines (REs). Note that all the engines are equipped with the buffer of certain size [29]. In this paper, we consider each link $(i, j) \in E$ as a bundled link consisting of multiple cables. For brevity, we shall use "link" instead of "bundled link" directly below. Each cable $(i, j)_k$ in (i, j) has a pre-amplifier (PRA), in-line amplifiers (ILAs), regenerators (REGs) and a post-amplifier (POA). For a more detailed description for the network model, readers may refer to our previous work [30]. The related notations of parameters and variables used in our paper are summarized in Table 1 and Table 2 respectively.

B. QoS CHARACTERIZATION

Based on the DiffServ model [31] and referring to ITU-T G.1010 [32], the qth type of application AP_q has its corresponding QoS requirement QoS_q. We characterize QoS_q as $\left(bw_q^{\min}, dl_q^{\max}, jt_q^{\max}, er_q^{\max}\right)$, where $bw_q^{\min}$, $dl_q^{\max}$, $jt_q^{\max}$ and $er_q^{\max}$ represent the requirements bounds of the bandwidth, delay, delay jitter and error rate respectively for the qth type of application AP_q, and can be set based on ITU-T G.1010. Specifically, the QoS provided by the node i is represented as a triple, namely $\langle dl_i, jt_i, er_i\rangle$, where dl_i, jt_i and er_i represent delay, delay jitter and error rate of the node i respectively, whereas the QoS provided by the link l is represented as a quadruple, namely $\langle bw_l, dl_l, jt_l, er_l\rangle$, where bw_l, dl_l, jt_l and er_l represent the available bandwidth, delay, delay jitter and error rate of link l respectively.

For a path $Path$, its provided QoS is calculated in Eqs. (1)-(4).

$$bw_{Path} = \min\{bw_l | l \in Path\} \tag{1}$$

$$dl_{Path} = \sum_{i\in Path} dl_i + \sum_{l\in Path} dl_l, \tag{2}$$

$$jt_{Path} = \sum_{i\in Path} jt_i + \sum_{l\in Path} jt_l \tag{3}$$

$$er_{Path} = 1 - \prod_{i\in Path} (1 - er_i) \times \prod_{l\in Path} (1 - er_l) \tag{4}$$

C. GREEN ROUTING IN BACKBONE NETWORKS WITH BUNDLED LINKS (GRB2)

In order to achieve substantial power savings over backbone networks with bundled links, we propose the minimization problem GRB2. In the problem, it is permitted to power off some network components to accomplish the overall power saving in the network. In this case, the network power consumption can be calculated by the following Eq. (5), as shown at the bottom of the page, where $P^{\text{port}}_{(i,j)_k}$ is set to $P^{\max}_{(i,j)_k}$.

Further, we divide the behaviors of the cables forming a bundled link into two kinds: Unified Behavior (UB) and Independent Behavior (IB). Specifically, the cables with UB are always powered on or off as a whole, and the ones with IB can be powered on or off independently each other. Thus

$$P_{net} = \sum_{i\in V} \left(\left(\left(P_i^{\text{ME}} + \sum_{u=1}^{N_i^{\text{CHA}}} \left(P_{i,u}^{\text{CHA}} \times ChaSt_i^u + \sum_{w=1}^{N_{i,u}^{\text{LC}}} \left((P_{i,u,w}^{\text{FE}} + P_{i,u,w}^{\text{RE}}) \times LcdSt_{i,u}^w \right) \right) \right) \times NodeSt_i \right) + \sum_{(i,j)\in E} \sum_{(i,j)_k\in(i,j)} \left(\left(P^{\text{port}}_{(i,j)_k} + \left(P^{\text{PRA}}_{(i,j)_k} + P^{\text{ILA}}_{(i,j)_k} \times N^{\text{ILA}}_{(i,j)_k} + P^{\text{REG}}_{(i,j)_k} \times N^{\text{REG}}_{(i,j)_k} + P^{\text{POA}}_{(i,j)_k} \right) \right) \times CableSt_{(i,j)_k} \right) \tag{5}$$

TABLE 1. Notations definition for parameters used in the following problem formulations.

Notation	Description
P_i^{ME}	the power consumption of the ME in node i
$P_{i,u}^{CHA}$	the power consumption of the uth CHA in node i
$P_{i,u,w}^{FE}$	the power consumption of the FE in the wth LC of the uth CHA in node i
$P_{i,u,w}^{RE}$	the power consumption of the RE in the wth LC of the uth CHA in node i
$P_{(i,j)_k}^{PRA}$	the power consumption of the PRA in the cable $(i,j)_k$
$P_{(i,j)_k}^{ILA}$	the power consumption of an ILA in the cable $(i,j)_k$
$P_{(i,j)_k}^{REG}$	the power consumption of a REG in the cable $(i,j)_k$
$P_{(i,j)_k}^{POA}$	the power consumption of the POA in the cable $(i,j)_k$
$P_{(i,j)_k}^{port}$	the port power consumption on the node i side of the cable $(i,j)_k$
N_i^{CHA}	the number of CHA in node i
$N_{i,u}^{LC}$	the number of LCs in the uth CHA of node i
$N_{i,u,w}^{port}$	the number of ports of the wth LC in the uth CHA of node i
$N_{(i,j)_k}^{ILA}$	the number of ILAs in the cable $(i,j)_k$
$N_{(i,j)_k}^{REG}$	the number of REGs in the cable $(i,j)_k$
$N_{(i,j)}$	the number of cables forming link (i,j)
$C_{(i,j)_k}^{port}$	the port capacity on one side of the cable $(i,j)_k$
$MCU_{(i,j)_k}$	the maximum utilization allowed of cable $(i,j)_k$
C_i^{N}	the capacity of node i

TABLE 2. Notations definition for variables used in the following problem formulations.

Notation	Description
$PortSt_{i,u,w}^t$	the state identifier of the tth port in the wth line card of the uth chassis in node i
$LcdSt_{i,u}^w$	the state identifier of the wth line card in the uth chassis of node i
$ChaSt_i^u$	the state identifier of the uth chassis in node i
$NodeSt_i$	the state identifier of node i
$CableSt_{(i,j)_k}$	the state identifier of the cable $(i,j)_k$ in link (i,j)
$n_{(i,j)}$	the number of powered-on cables in link (i,j)
D	the set of the source-destination pairs in the traffic matrix
$TD_{s,d}$	the traffic demand between source node s and destination node d
$TD_{(i,j)}^{s,d}$	the traffic demand between source node s and destination node d flowing through link (i,j)
$\boldsymbol{TDS}_{(i,j)}$	the set of the traffic demands flowing through link (i,j)
$Size\left(\boldsymbol{TDS}_{(i,j)}\right)$	the total size of the traffic demands in $\boldsymbol{TDS}_{(i,j)}$
$f_{(i,j)_k}^{s,d}$	the amount of $TD_{s,d}$ flowing through the cable $(i,j)_k$ in link (i,j)
T_i	the traffic throughput of node i

we divide GRB2 into two sub-problems: one where the cables have the characteristic of UB, referred to as GRB2_UB, and the other one where the cables have the characteristic of IB, referred to as GRB2_IB.

1) GRB2_UB

The cables forming a bundled link are all active at the maximum rate or all inactive, and GRB2_UB can be thus formulated as the following Mixed Integer Linear Programming (MILP) model.

$$\textit{Minimize } P_{net} \tag{6}$$

$$\text{Subject to } \sum_{(i,j)\in E}\sum_{(i,j)_k\in(i,j)} f_{(i,j)_k}^{s,d} - \sum_{(i,j)\in E}\sum_{(i,j)_k\in(i,j)} f_{(i,j)_k}^{s,d} = \begin{cases} TD_{s,d}, & i=s \\ -TD_{s,d}, & i=d \\ 0, & \forall i\in\{V-s-d\}, \end{cases}$$

$$\forall s,\ d \in D \tag{7}$$

$$f_{(i,j)_k}^{s,d} \geq 0, \quad \forall (i,j)_k \in (i,j),\ \forall (i,j) \in E, \quad \forall s,\ d \in D \tag{8}$$

$$T_i = \sum_{(i,j)\in E} \sum_{(i,j)_k \in (i,j)} \sum_{s,d\in D} f_{(i,j)_k}^{s,d} + \sum_{s,i} TD_{s,i} \leq C_i^{\mathrm{N}} \times NodeSt_i, \quad \forall i \in V \tag{9}$$

$$\sum_{s,d\in D} \sum_{(i,j)_k\in(i,j)} f_{(i,j)_k}^{s,d} \leq \sum_{(i,j)_k\in(i,j)} MCU_{(i,j)_k} \times C_{(i,j)_k}^{\mathrm{port}} \times CableSt_{(i,j)_k}, \quad \forall (i,j) \in E \tag{10}$$

$$\sum_{(i,j)\in E} n_{(i,j)} \leq \sum_{(i,j)\in E} N_{(i,j)} \times NodeSt_i, \quad \forall i \in V \tag{11}$$

$$ChaSt_i^u,\ LcdSt_{i,u}^w,\ PortSt_{i,u,w}^t,\ NodeSt_i \text{ and } CableSt_{(i,j)_k} \in \{0,1\}, \quad \forall i \in V, \quad \forall (i,j)_k \in (i,j) \tag{12}$$

$$\sum_{t=1}^{N_{i,u,w}^{\mathrm{port}}} PortSt_{i,u,w}^t \leq N_{i,u,w}^{\mathrm{port}} \times LcdSt_{i.u}^w, \quad \forall i \in V \tag{13}$$

$$\sum_{w=1}^{N_{i,u}^{\mathrm{LC}}} LcdSt_{i,u}^w \leq N_{i,u}^{\mathrm{LC}} \times ChaSt_i^u, \quad \forall i \in V \tag{14}$$

$$\sum_{u=1}^{N_i^{\mathrm{CHA}}} ChaSt_i^u \leq N_i^{\mathrm{CHA}} \times NodeSt_i, \quad \forall i \in V \tag{15}$$

$$n_{(i,j)} = \sum_{(i,j)_k\in(i,j)} CableSt_{(i,j)_k} \in \left\{0, N_{(i,j)}\right\}, \quad \forall (i,j) \in E \tag{16}$$

$$bw_{Path_{s,d}} \geq bw_u^{\min}, \quad \forall s,\ d \in D \tag{17}$$

$$dl_{Path_{s,d}} \leq dl_u^{\max}, \quad \forall s,\ d \in D \tag{18}$$

$$jt_{Path_{s,d}} \leq jt_u^{\max}, \quad \forall s,\ d \in D \tag{19}$$

$$er_{Path_{s,d}} \leq er_u^{\max}, \quad \forall s,\ d \in D \tag{20}$$

Eq. (7) is the classical flow conservation constraints. Eq. (8) is the flow variables constraints. Eqs. (9) and (10) are the extended node and link capacity constraints respectively. Eq. (11) dictates that a node can be powered off only when all the incident links are powered off. Eq. (12) defines the binary variables identifying components status (value "1" denotes the powered on status and value "0" denotes the powered off status). Eqs. (13)-(15) dictate a line card/chassis/node can be powered off only when all the ports/line cards/chassis in it are powered off. Eq. (16) imposes only entire links can be powered off. Eqs. (17)-(20) are the corresponding QoS constraints for the routing solving paths $Path_{s,d}$ of the traffic demands $TD_{s,d}$ belonging to the uth type of application.

2) GRB2_UB

Each cable in a bundled link can be active at a maximum rate or inactive independently, and GRB2_IB can be thus formulated as the following MILP model.

$$\text{Minimize } P_{net}$$
$$\text{Subject to Eqs. (7)-(15) and (17)-(20).} \tag{21}$$

IV. HEURISTICS

The MILP models of GRB2_UB and GRB2_IB fall in the class of NP-hard problems [17], and thus we exploit multi-stage power-aware intelligent adaptive heuristics TEPG to solve them. Further, we split TEPG into two parts: the hop-by-hop Green Greedy Routing stage (GGR) and the Traffic Assignment stage inside the Bundled links (TAB). The rest of this section is devoted to the description of the heuristics.

Algorithm TEPG

Input: $G, D, TD_{s,d}$
Output: $\left\{G^{(n)}, \boldsymbol{Route}, \boldsymbol{Sol}\right\}$ or *Null*

$\boldsymbol{Route} \leftarrow \emptyset$, $\boldsymbol{Sol} \leftarrow \emptyset$;
Do ACNN;
If the output in ACNN is *Null* **then**
  Return *Null*;
End If
Do GP four times for four combined node-link sorting criteria, and obtain the best solution with the smallest network sub-graph among them;
If there have been nodes or links powered off in GP **then**
  Do
    Do FC;
    Do GC four times for four combined node-link sorting criteria, and obtain the best solution with the smallest network sub-graph among them;
  While there have been nodes or links powered off in GC;
  End Do
End If
If GRB2_UB **then**
  Do TAB_LU;
  Return $\left\{G^{(n)}, \boldsymbol{Route}, \boldsymbol{Sol}\right\}$;
End If
If GRB2_IB **then**
  Do TAB_LI;
  Return $\left\{G^{(n)}, \boldsymbol{Route}, \boldsymbol{Sol}\right\}$;
End If

A. DEFINITIONS AND NOTATIONS FOR HEURISTICS

Definition 1 (Available Capacity (AC) of a Link/Node): In a link (i,j)/node i, let its Total Capacity (TC) and Occupied Capacity (OC) are denoted as $TC_{(i,j)}/TC_i$ and $OC_{(i,j)}/OC_i$ respectively, then the residual capacity between them is referred as Available Capacity (AC) of link (i, j)/node i, namely $AC_{(i,j)} = TC_{(i,j)} - OC_{(i,j)}$ and $AC_i = TC_i - OC_i$.

Definition 2 (QoS Tabu Node): During the process of routing traffic demand TD, assuming the current hop node is i, if a certain QoS constraint will be violated when a next hop node j added into the current solving route $\boldsymbol{Route}_{s,d}$, then the newly added node j is referred as a QoS tabu node of i for $\boldsymbol{Route}_{s,d}$ and we mark the set of all the QoS tabu nodes of i for $\boldsymbol{Route}_{s,d}$ as $\boldsymbol{QTN}_i^{\boldsymbol{Route}_{s,d}}$.

B. GREEN GREEDY ROUTING (GGR)

GGR is divided into four stages: (i) an Available Capacity of Neighbor Nodes based hop-by-hop routing stage (ACNN), (ii) a Greedy Pruning stage (GP), (iii) a Feasible Checking stage for routing (FC) and (iv) a Greedy Checking stage for pruning (GC).

1) AVAILABLE CAPACITY OF NEIGHBOR NODES BASED HOP-BY-HOP ROUTING STAGE (ACNN)

In this stage, we try to power off as many network components as possible to obtain the smallest sub-graph sufficient to route all the traffic demands in D. We try to obtain an exquisite initial solution so that the computational overhead can be reduced as much as possible at the following stages.

For each Next Hop Node (NHN), we select the node with the minimum AC in all the neighbor nodes of the Current Hop Node (CHN). ACNN is described as follows, where v_c and v_p denote the current hop node and the previous hop node respectively; $\boldsymbol{NEI}_k$ denotes the set of neighbor nodes for k; $\boldsymbol{NCA}_k^{\boldsymbol{Route}_{s,d}}$ denotes the set of candidate nodes of k for $\boldsymbol{Route}_{s,d}$, $\boldsymbol{NCA}_k^{\boldsymbol{Route}_{s,d}} = \boldsymbol{NEI}_k - \boldsymbol{Route}_{s,d} - \boldsymbol{QTN}_k^{\boldsymbol{Route}_{s,d}}$.

As an example, we consider the network graph G in Fig. 2(a) with five traffic demands 1-5. We sorted these demands in a descending order according to the amount of traffic exchanged: $TD_{0,14}$, $TD_{1,9}$, $TD_{3,10}$, $TD_{4,13}$ and $TD_{5,8}$, whose sizes are 3, 2.5, 2, 1.5 and 1 respectively. Their application types are VOD, video conference, cyber game, IPTV and VoIP respectively, and the corresponding QoS requirements are $QoS_{type_1} = (2.6\text{Mbps}, 300\text{ms}, 60\text{ms}, 0.1\%)$, $QoS_{type_2} = (384\text{Kbps}, 400\text{ms}, 100\text{ms}, 1\%)$, $QoS_{type_3} = (10Kbps, 200\text{ms}, 40\text{ms}, 0.01\%)$, $QoS_{type_4} = (2\text{Mbps}, 220\text{ms}, 50\text{ms}, 0.1\%)$, and $QoS_{type_5} = (36\text{Kbps}, 160\text{ms}, 30\text{ms}, 2\%)$ respectively. The number of cables in each link and the capacity of each cable are given in Table 3. Furthermore, note that all cables are active for GRB2_UB, and at the initial state of the sample network, we assume that the cables whose capacity is more than 1 are active and the others are sleeping for GRB2_IB.

The process of routing and pruning at the stage of ACNN is shown from Fig. 2(b) to Fig. 2(g). For clarity, the results of selecting operation in each hop of routing are tabulated in Table 4, where QC denotes QoS Constraints and BT denotes BackTracking. Finally, we route all the demands under the QoS constraints over the network graph G by $\boldsymbol{Route} \leftarrow \{\boldsymbol{Route}_{0,14}, \boldsymbol{Route}_{1,9}, \boldsymbol{Route}_{3,10}, \boldsymbol{Route}_{4,13}, \boldsymbol{Route}_{5,8}\}$. Next,

Algorithm ACNN

Input: G, D, $TD_{s,d}$
Output: $\{G', \boldsymbol{Route}\}$ or *Null*

Sort $TD_{s,d}s, d \in D$ according to the size of traffic exchanged between each pair of source node and destination node from the largest one to the smallest one: $TD_{s_1,d_1}, TD_{s_2,d_2}, \ldots, TD_{s_{|D|},d_{|D|}}$;
For TD_{s_i,d_i} $(i \leftarrow 1 : |D|)$ **do**
  Obtain the sub-graph $G^{-i}_{-1-2-\cdots-(i-1)}$ by removing the nodes and the links, whose AC are smaller than TD_{s_i,d_i} or provided QoS cannot satisfy the QoS requirements of TD_{s_i,d_i}, from $G_{-1-2-\cdots-(i-1)}$ $(G_0 == G)$;
  For each $k \in G^{-i}_{-1-2-\cdots-(i-1)}$ **do**
    Obtain $\boldsymbol{NEI}_k$ of k, $\boldsymbol{QTN}_k^{\boldsymbol{Route}_{s,d}} \leftarrow \emptyset$;
  End For
  $\boldsymbol{Route}_{s_i,d_i} \leftarrow \boldsymbol{Route}_{s_i,d_i} \cup \{s_i\}$, $v_c \leftarrow s_i$;
  While $d_i \notin \boldsymbol{Route}_{s_i,d_i}$ **do**
    If $\forall j \in \boldsymbol{NCA}_{v_c}^{\boldsymbol{Route}_{s_i,d_i}}$, $\exists j == d_i$ **then**
      $\boldsymbol{Route}_{s_i,d_i} \leftarrow \boldsymbol{Route}_{s_i,d_i} \cup \{d_i\}$;
    Else If $\boldsymbol{NCA}_{v_c}^{\boldsymbol{Route}_{s_i,d_i}} == \emptyset$ **then**
      If $v_c == s_i$ **then**
        Return *Null*;
      Else If $(\boldsymbol{NEI}_{v_c} - \boldsymbol{Route}_{s_i,d_i}) == \emptyset$ **then**
        $\boldsymbol{NEI}_{v_p} \leftarrow (\boldsymbol{NEI}_{v_p} - v_c)$,
        $\boldsymbol{Route}_{s_i,d_i} \leftarrow (\boldsymbol{Route}_{s_i,d_i} - v_c)$, and backtrack from v_c to the previous hop node v_p, namely $v_c \leftarrow v_p$;
        Continue;
      Else
        $\boldsymbol{Route}_{s_i,d_i} \leftarrow (\boldsymbol{Route}_{s_i,d_i} - v_c)$,
        $\boldsymbol{QTN}_{v_p}^{\boldsymbol{Route}_{s_i,d_i}} \leftarrow \boldsymbol{QTN}_{v_p}^{\boldsymbol{Route}_{s_i,d_i}} \cup \{v_c\}$, and backtrack from v_c to the previous hop node v_p, namely $v_c \leftarrow v_p$;
        Continue;
      End If
    End If
    Else If the node $j^{C_{\min}}$ with the minimum AC in $\boldsymbol{NCA}_{v_c}^{\boldsymbol{Route}_{s_i,d_i}}$ is a sole one **then**
      Select the node $j^{C_{\min}}$ with the minimum AC as the next hop node, $v_c \leftarrow j^{C_{\min}}$,
      $\boldsymbol{Route}_{s_i,d_i} \leftarrow \boldsymbol{Route}_{s_i,d_i} \cup \{j^{C_{\min}}\}$;
    Else
      Select the node $j^{LC_{\min}}$ whose incident link with minimum AC from $\{j^{C_{\min}}\}$ as the next hop node, $v_c \leftarrow j^{LC_{\min}}$,
      $\boldsymbol{Route}_{s_i,d_i} \leftarrow \boldsymbol{Route}_{s_i,d_i} \cup \{j^{LC_{\min}}\}$;
    End If
  End If
End If
If the QoS constraints (17)-(20) are not satisfied by the $\boldsymbol{Route}_{s_i,d_i}$ **then**
  $\boldsymbol{Route}_{s_i,d_i} \leftarrow (\boldsymbol{Route}_{s_i,d_i} - v_c)$,
  $\boldsymbol{QTN}_{v_p}^{\boldsymbol{Route}_{s_i,d_i}} \leftarrow \boldsymbol{QTN}_{v_p}^{\boldsymbol{Route}_{s_i,d_i}} \cup \{v_c\}$, and backtrack

from v_c to the previous hop node v_p, namely $v_c \leftarrow v_p$;
End If
End While
Subtract the size of TD_{s_i,d_i} from the capacity of each edge and each node along the $\boldsymbol{Route}_{s_i,d_i}$ in $G_{-1-2......-(i-1)}$, recover the nodes and the edges whose AC are smaller than TD_{s_i,d_i} in $G_{-1-2......-(i-1)}$ and mark the modified network graph as $G_{-1-2......-i}$;
$\boldsymbol{Route} \leftarrow \boldsymbol{Route} \cup \boldsymbol{Route}_{s_i,d_i}$;
End For
Obtain G' by removing the edges and nodes unused to transit any traffic demands from $G_{-1-2......-|D|}$;
Return $\{G', \boldsymbol{Route}\}$.

we can obtain G' shown in Fig. 2(h) by removing (0, 1) and (4, 6) not used to transit any traffic demands from $G_{-1-2-3-4-5}$.

2) GREEDY PRUNING STAGE (GP)

In the stage, we aim to obtain a sub-network powered with lower energy consumption. GP proceeds as follows: first sort nodes and links according to some criteria, then try to switch off as many nodes and links as possible in this order. Due to the energy saving achieved by switching off nodes is higher than by switching off links, nodes are therefore considered to be powered off before links.

Two sorting criteria, namely Least-Degree (LD) and Least-Flow (LF), are adopted to iterate through the node set. Nodes are sorted in a non-decreasing order according to, respectively, the total number of incident links and outgoing links to each node and the amount of traffic flowing through each node. Note that, if the degrees of some nodes are exactly equal, we sort them according to the least degrees of the neighbor nodes of the node under consideration, which is referred to as Secondary Degree (SD) of a node; similarly, if the amount of traffic flowing through some nodes is exactly equal, we sort them according to the least amount of traffic flowing through the neighbor nodes of the node under consideration, which is referred to as Secondary Flow (SF) of a node.

Also two sorting criteria, namely Least-Adjacent-Degree (LAD) and Least-Flow (LF), are considered to power off links. The LAD criterion sorts the links in a non-decreasing order according to the total number of incident links and outgoing links to two end nodes adjacent to each link, which are referred to as Adjacent Degree (AD) of a link. The LF criterion sorts links in a non-decreasing order according to the amount of carried traffic in each link. Note that, if the adjacent degrees of some links are exactly equal, we sort them according to the least degrees of the neighbor nodes of two end nodes adjacent to the link under consideration, which is referred to as Secondary Adjacent Degree (SAD) of a link; similarly, if the amount of traffic flowing through some links is exactly equal, we sort them according to the least amount of traffic flowing through two end nodes adjacent to the link under consideration, which is referred to as the Adjacent Flow (AF) of a link.

TABLE 3. Structure and characteristics of links in the sample network.

(i,j)	$C_{(i.j)}$	$N_{(i.j)}$	$(i.j)_1$	$(i.j)_2$	$(i.j)_3$	$(i.j)_4$	$(i.j)_5$	$(i.j)_6$
(0,1)	6.5	6	2	1.5	1	1	0.5	0.5
(0,2)	1.5	2	1	0.5	—	—	—	—
(0,3)	7	6	2	1.5	1.5	1	0.5	0.5
(0,4)	5.5	5	2	1.5	1	0.5	0.5	—
(1,5)	6	5	2	1.5	1	1	0.5	—
(2,5)	4	4	1.5	1	1	0.5	—	—
(3,6)	5.5	5	2	1.5	1	0.5	0.5	—
(4,6)	3.5	3	2	1	0.5	—	—	—
(4,7)	4	4	1.5	1	1	0.5	—	—
(5,10)	3.5	3	2	1	0.5	—	—	—
(6,8)	7	6	2	1.5	1.5	1	0.5	0.5
(6,9)	2.5	3	1	1	0.5	—	—	—
(7,9)	6	5	2	1.5	1	1	0.5	—
(8,11)	5	4	2	1.5	1	0.5	—	—
(8,12)	7	6	2	1.5	1.5	1	0.5	0.5
(9,12)	5	4	2	1.5	1	0.5	—	—
(10,13)	9	6	2	2	1.5	1.5	1	1
(11,13)	5	4	2	1.5	1	0.5	—	—
(11,14)	8	5	2	2	1.5	1.5	1	—
(12,14)	5.5	5	2	1.5	1	0.5	0.5	—
(13,14)	4	4	1.5	1	1	0.5	—	—

In practice, due to the degree is a positive integer in a narrow value range, it is likely to encounter the same value whether for LD sorting in nodes or for LAD sorting in links even for a secondary sorting via SD or SAD. In contrast, due to the amount of traffic changes in a broad range, the equal situations are hardly encountered for LF sorting in nodes and links, especially for a secondary sorting via SF or AF. Under the circumstances, for LD sorting and LAD sorting we have to devise two further sorting criteria, that is, the Least-Occupied-Capacity (LOC) and the Least-Adjacent-Occupied-Capacity (LAOC), respectively. The LOC criterion sorts the nodes according to the occupied capacity of each node. The LAOC criterion sorts the links according to the arithmetic average occupied capacity of two end nodes adjacent to each link. So if the degrees of some nodes or some links via the secondary sorting of SD or SAD is still equal, we sort the nodes according to LOC and the links according to LAOC.

GP tries to power off nodes first, and then links are considered in a secondary round of iteration. So the four combined

TABLE 4. Hop-by-hop routing via ACNN in the sample network.

TD	CHN	*NEI*	NHN	$Route_{s_i,d_i}$	QoS_{s_i,d_i}	QC	BT
$TD_{0,14}$	0	{1,3,4}	4	{0,4}	(5.5,45,8,0)	✓	×
	4	{6,7}	7	{0,4,7}	(4,90,15,0)	✓	×
	7	{9}	9	{0,4,7,9}	(4,140,22,0)	✓	×
	9	{12}	12	{0,4,7,9,12}	(4,165,26,0)	✓	×
	12	{8,14}	14	{0,4,7,9,12,14}	(4,205,31,0)	✓	×
$TD_{1,9}$	1	{0,5}	5	{1,5}	(6,50,8,0)	✓	×
	5	{2,10}	2	—	—	—	✓ (until 5)
	5	{10}	10	{1,5,10}	(3.5,80,13,0)	✓	×
	10	{13}	13	{1,5,10,13}	(3.5,95,16,0)	✓	×
	13	{11,14}	11	{1,5,10,13,11}	(3.5,125,21,0)	✓	×
	11	{8,14}	14	{1,5,10,13,11,14}	(3.5,145,24,0)	✓	×
	14	{12}	12	{1,5,10,13,11,14,12}	(2.5,190,30,0)	✓	×
	12	{8}	8	{1,5,10,13,11,14,12,8}	(2.5,220,34,0)	✓	×
	8	{6}	6	{1,5,10,13,11,14,12,8,6}	(2.5,240,37,0)	✓	×
	6	{3,4,9}	9	{1,5,10,13,11,14,12,8,6,9}	(2.5,280,43,0)	✓	×
$TD_{3,10}$	3	{0,6}	0	{3,0}	(7,60,10,0)	✓	×
	0	{1,4}	4	{3,0,4}	(2.5,85,14,0)	✓	×
	4	{6}	6	{3,0,4,6}	(2.5,115,26,0)	✓	×
	6	{8}	8	{3,0,4,6,8}	(2.5,135,29,0)	✓	×
	8	{11,12}	12	{3,0,4,6,8,12}	(2.5,170,34,0)	✓	×
	12	{9}	9	{3,0,4,6,8,12,9}	(2,200,39,0)	✓	×
	9	{7}	7	—	—	—	✓ (until 8)
	8	{11}	11	{3,0,4,6,8,11}	(2.5,160,34,0)	✓	×
	11	{13,14}	13	{3,0,4,6,8,11,13}	(2.5,180,37,0)	✓	×
	13	{10,14}	10	{3,0,4,6,8,11,13,10}	(2.5,205,42,0)	×	✓ (until 13)
	13	{14}	14	—	—	—	✓ (until 11)
	11	{14}	14	{3,0,4,6,8,11,14}	(2.5,180,37,0)	✓	×
	14	{13}	13	{3,0,4,6,8,11,14,13}	(2.5,195,40,0)	✓	×
	13	{10}	10	{3,0,4,6,8,11,14,13,10}	(2.5,220,45,0)	×	✓ (until 0)
	0	{1}	1	{3,0,1}	(6.5,80,13,0)	✓	×
	1	{5}	5	{3,0,1,5}	(3.5,120,19,0)	✓	×
	5	{2}	2	—	—	—	✓ (until 3)
	3	{6}	6	{3,6}	(5.5,45,7,0)	✓	×
	6	{4,8}	4	{3,6,4}	(3.5,80,20,0)	✓	×
	4	{0}	0	—	—	—	✓ (until 6)
	6	{8}	8	{3,6,8}	(4.5,65,10,0)	✓	×
	8	{11}	11	{3,6,8,11}	(4.5,90,15,0)	✓	×
	11	{13,14}	13	{3,6,8,11,13}	(2.5,110,18,0)	✓	×
	13	{10,14}	10	{3,6,8,11,13,10}	(2.5,135,23,0)	✓	×
$TD_{4,13}$	4	{0,6}	0	{4,0}	(2.5,45,8,0)	✓	×
	0	{1,2,3}	2	{4,0,2}	(1.5,60,11,0)	✓	×
	2	{5}	5	{4,0,2,5}	(1.5,85,16,0)	✓	×
	5	{1}	1	—	—	—	✓ (until 0)
	0	{1,3}	3	{4,0,3}	(2.5,85,14,0)	✓	×
	3	{6}	6	{4,0,3,6}	(2.5,110,17,0)	✓	×
	6	{8}	8	{4,0,3,6,8}	(2.5,130,20,0)	✓	×
	8	{11,12}	12	{4,0,3,6,8,12}	(2.5,165,25,0)	✓	×
	12	{9}	9	{4,0,3,6,8,12,9}	(2,195,30,0)	✓	×
	9	{7}	7	—	—	—	✓ (until 8)
	8	{11}	11	{4,0,3,6,8,11}	(2.5,155,25,0)	✓	×
	11	{14}	14	{4,0,3,6,8,11,14}	(2.5,175,28,0)	✓	×
	14	{13}	13	{4,0,3,6,8,11,14,13}	(2.5,190,31,0)	✓	×
$TD_{5,8}$	5	{1,2,10}	2	{5,2}	(4,35,7,0)	✓	×
	2	{0}	0	{5,2,0}	(1.5,60,12,0)	✓	×
	0	{1,3,4}	4	{5,2,0,4}	(1,85,16,0)	✓	×
	4	{7}	7	{5,2,0,4,7}	(1,130,23,0)	✓	×
	7	{9}	9	{5,2,0,4,7,9}	(1,180,30,0)	×	✓ (until 0)
	0	{1,3}	3	{5,2,0,3}	(1.5,100,18,0)	✓	×
	3	{6}	6	{5,2,0,3,6}	(1.5,125,21,0)	✓	×
	6	{4,8}	8	{5,2,0,3,6,8}	(1,145,24,0)	✓	×

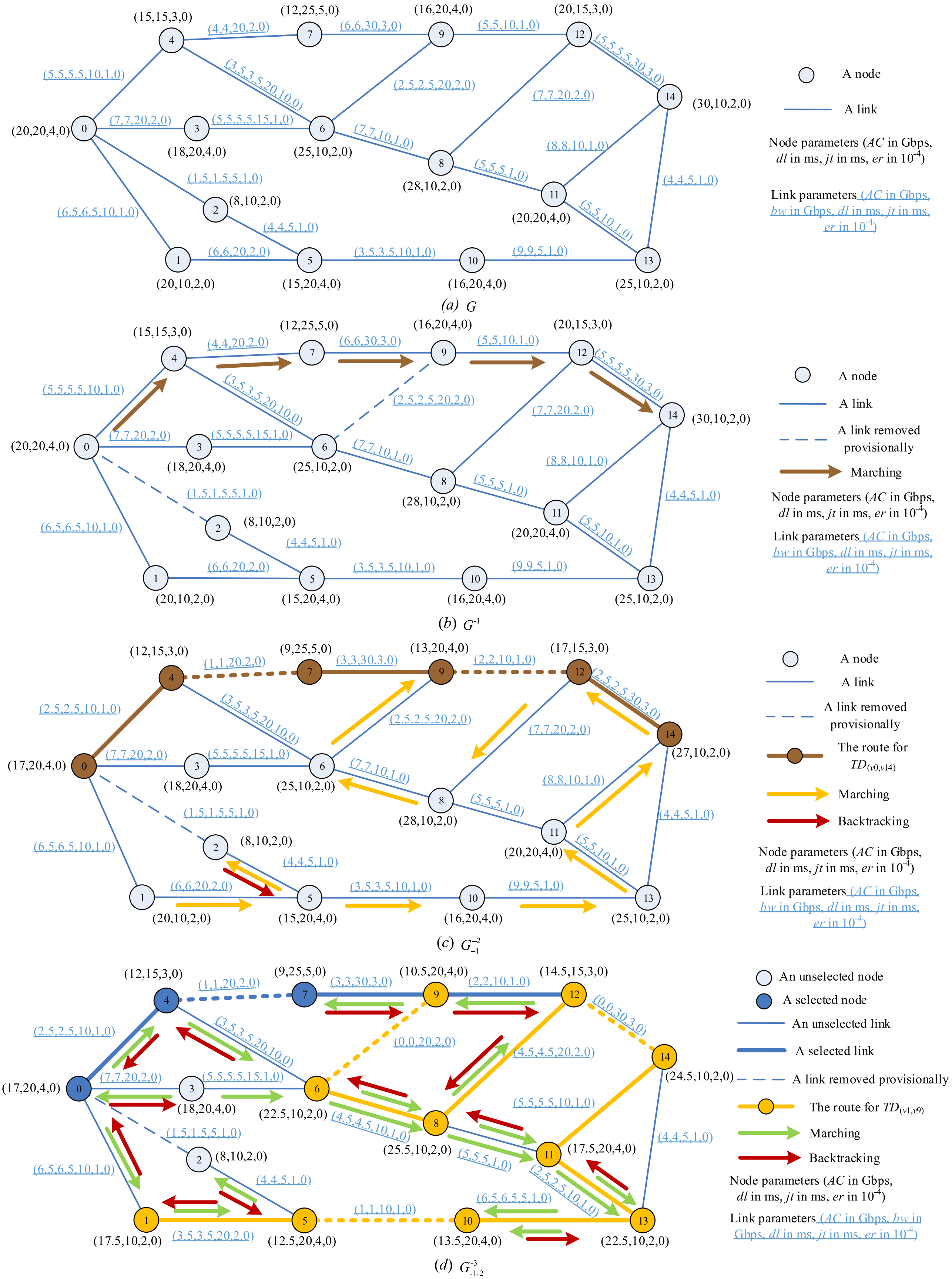

FIGURE 2. Process of routing and pruning at the stage of ACNN.

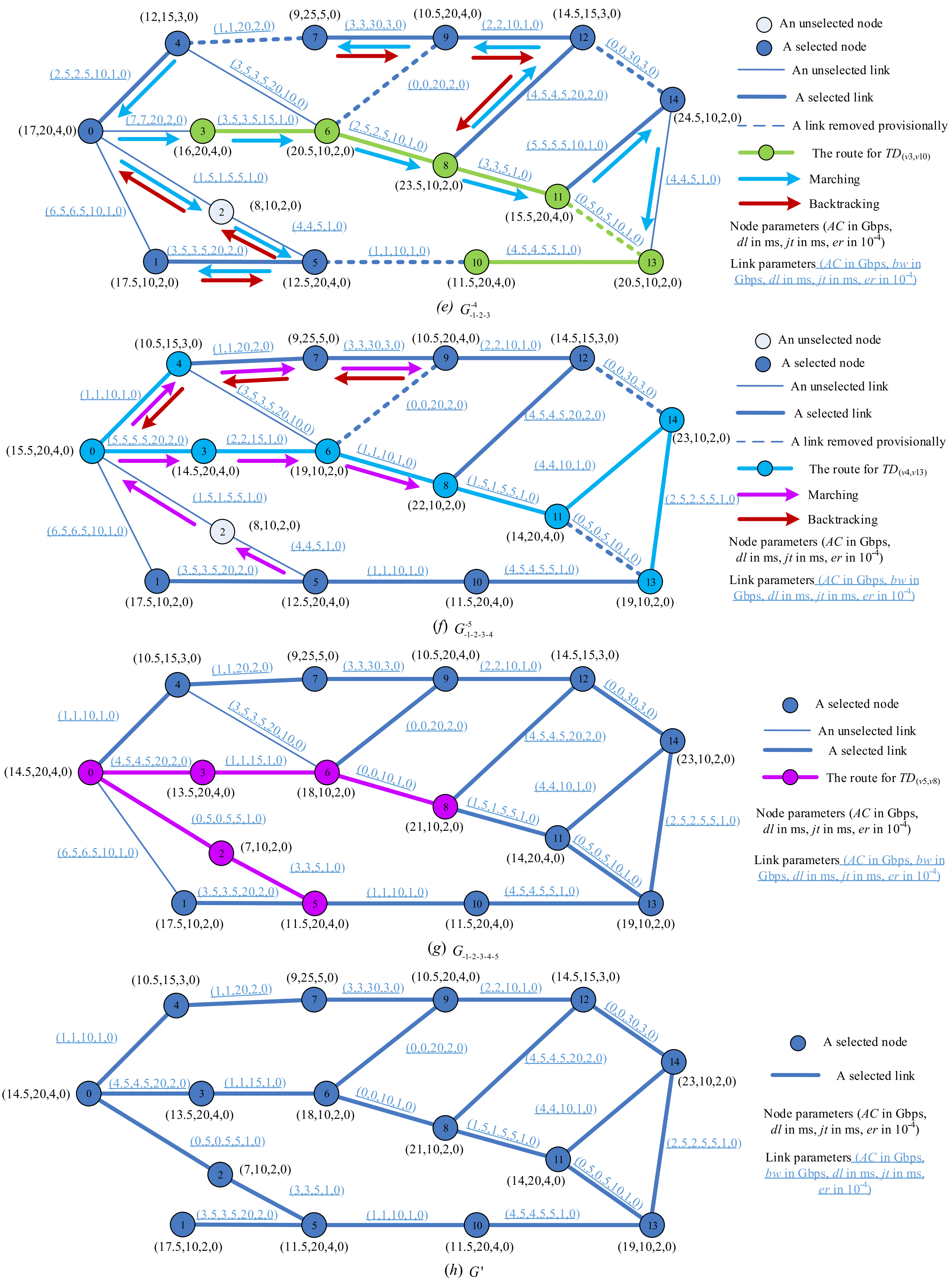

FIGURE 2. *(Continues.)* **Process of routing and pruning at the stage of ACNN.**

node-link sorting criteria are LD-LAD, LD-LF, LF-LAD and LF-LF.

At each step of the iteration, we verify whether the next active network element according to the sorting order can be powered off. The considered element can be actually powered off if the rerouting on the reduced network is able to support all traffic demands and no violation for QoS constraints. The stage will terminate when all the network elements have been tested.

The stage is, once for each combined node-link sorting criterion, run four times, and returns the solution with the smallest energy consumption among them. GP is described as follows.

In practice, besides these criteria, we also tested the corresponding ones in a decreasing order. Since all the criteria adopting inverted order perform worse, we omit them in this paper.

Following the above example, based on G' and ***Route*** obtained in the stage of ACNN, we first consider the nodes sorting. Obviously, the source nodes and the destination nodes of all the traffic demands cannot be powered off. Now we sort the remainder nodes according to the criteria of LD and LF in Table 5.

TABLE 5. LD/LF based nodes sorting over G'.

Nodes	D-SD-OC	LD Sorting	Flow	LF Sorting
2	2-6	2	2	1
6	3-8	3	14	5
7	2-5	1	6	2
11	3-9-6	5	12	4
12	3-9-5.5	4	11	3

According to the LD based nodes sorting shown in Table 5, we try to power off the nodes in the order of 7, 2, 6, 12, and 11. Process of routing and powering off according to the LD based nodes sorting at the stage of GP is shown from Fig. 3(a) to Fig. 3(e). Finally, the checking results are summarized in Table 6, where CN denotes connectivity and for the LD based nodes sorting, we get an updated ***Route*** and $G'^{-v_2}_{+5-5}$.

According to the LF based nodes sorting shown in Table 5, we try to power off the nodes in the order of 2, 7, 12, 11, and 6. By comparing the nodes sorting between LD and LF, obviously, we know node 2 can still do under LF sorting criterion according to the result of LD sorting criterion. Now we try to power off node 7, and there is only the route $\boldsymbol{Route}_{0,14}$ of the traffic demand $TD_{0,14}$ passing through node 7. After recovering the capacity "$TD_{0,14} = 3$" of the nodes and links along $\boldsymbol{Route}_{0,14}$, and removing node 7, (4, 7), (7, 9) and the edges unable to accommodate $TD_{0,14}$ from $G'^{-v_2}_{+5-5}$, we obtain the network graph $G'^{-v_2-v_7-1}_{+5-5+1}$ shown in Fig. 3(f). The connectivity between node 0 and node 14 has been broken and thus node 7 cannot be powered off. As for node 12, node 11, and node 6, although their order has changed compared with that

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Algorithm GP

Input: G', D, $TD_{s,d}$, ***Route***

Output: $\{G''$, ***Route***$\}$

Sort the nodes neither the source nodes nor the destination nodes of all the traffic demands in G' according to the corresponding criterion (LD or LF): $i \leftarrow 1 : |V|_{G'}$;
For $i \leftarrow 1 : |V|_{G'}$ **do**
  Sort the traffic demands flowing through i from the largest size to the smallest one: $TD_i^1, TD_i^2, \ldots, TD_i^{i_n}$;
  Recover the occupied capacity of the nodes and the links along the routes to accommodate $TD_i^1, TD_i^2, \ldots, TD_i^{i_n}$, and remove i and the links adjacent to i from G';
  For TD_i^k $(k \leftarrow 1 : |i_n|)$ **do**
    If TD_i^k can be rerouted by adopting ACNN and QoS constraints (17)-(20) are not violated **then**
      Subtract the capacity of "TD_i^k" size from the nodes and the links along the modified route, update G' and ***Route***;
    Else
      Add i and the links adjacent to i back to G', still use the previous routes to accommodate $TD_i^1, TD_i^2, \ldots, TD_i^{i_n}$, and subtract the corresponding capacity from the nodes and the links along the previous routes;
      Break;
    End If
  End For
End For
Sort the links except for the sole links connecting the source nodes and the sole ones connecting the destination nodes of all the traffic demands in G' according to the corresponding criterion (LAD or LF): $j \leftarrow 1 : |E|_{G'}$;
For $j \leftarrow 1 : |E|_{G'}$ **do**
  Sort the traffic demands flowing through j from the largest size to the smallest one: $TD_j^1, TD_j^2, \ldots, TD_j^{j_m}$;
  Recover the occupied capacity of the nodes and the links along the routes to accommodate $TD_j^1, TD_j^2, \ldots, TD_j^{j_m}$, and remove j from G';
  For TD_j^u $(u \leftarrow 1 : |j_m|)$ **do**
    If TD_j^u can be rerouted by adopting ACNN and QoS constraints (17)-(20) are not violated **then**
      Subtract the capacity of "TD_j^u" size from the nodes and the links along the modified route, update G' and ***Route***;
    Else

Add j back to G', still use the previous routes to accommodate $TD_j^1, TD_j^2, \ldots, TD_j^{jm}$, and subtract the corresponding capacity from the nodes and the links along the previous routes;
Break;
End If
End For
End For
$G'' \leftarrow G'$;
Return $\{G'', \boldsymbol{Route}\}$.

TABLE 6. Checking for possibility to power off nodes according to LD.

Nodes checked	TDs Impacted	CN?	A new route & QoS	QC
7	$TD_{0,14}$	×	—	—
2	$TD_{5,8}$	✓	{5,10,13,14,11,8} (1,125,23,0)	✓
6	$TD_{1,9}$	×	—	—
	$TD_{3,10}$	—	—	—
	$TD_{4,13}$	—	—	—
12	$TD_{0,14}$	×	—	—
	$TD_{1,9}$	—	—	—
11	$TD_{1,9}$	✓	{1,5,10,13,14,12,8,6,9} (2.5,245,38,0)	✓
	$TD_{3,10}$	×	—	—
	$TD_{4,13}$	—	—	—
	$TD_{5,8}$	—	—	—

TABLE 7. Checking for possibility to power off nodes according to LF.

Nodes checked	TDs Impacted	CN?	A new route & QoS	QC
2	$TD_{5,8}$	✓	{5,10,13,14,11,8} (1,125,23,0)	✓
7	$TD_{0,14}$	×	—	—
12	Having the identical case to node 12 in Table 6			
11	Having the identical case to node 11 in Table 6			
6	Having the identical case to node 6 in Table 6			

of LD, it will not have any impacts to the result of powering off from the fact that none of these nodes can be powered off and thus there is no effect on the subsequent nodes. Finally, the checking results are summarized in Table 7. Hence, for the LF based nodes sorting, we get the same ***Route*** and $G_{+5-5}^{'-v_2}$ as that of the LD based nodes sorting.

Now, we pay attention to the links sorting. Obviously, the sole links ((1, 5), (5, 10) and (10, 13)) connecting the source nodes or the destination nodes of all the traffic demands cannot be powered off. Further, by observing $G_{+5-5}^{'-v_2}$ and ***Route*** obtained above carefully, we conclude none of three pairs of links, (13, 14) and (11, 13), (6, 8) and (9, 12), and (12, 14) and (8, 11), can be also powered off owing to the fact that the traffic demands flowing through any pair of links are inevitably routed through both of two links, either of which cannot accommodate the traffic demands. Now, we sort the remainder links according to the criteria of LAD and LF in Table 8.

TABLE 8. LAD/LF based link sorting over $G_{+5-5}^{'-v_2}$.

Links	AD-SAD-AOC	LAD Sorting	Flow-AF	LF Sorting
(0,3)	4-5-4	3	1.5	1
(0,4)	4-4	1	4.5	7
(3,6)	5-8-4.75	5	3.5	6
(4,7)	4-5-3.75	2	3-13.5	4
(6,9)	6-10	7	2.5-20.5	2
(7,9)	5-8-4.25	4	3-14.5	5
(8,12)	6-12	8	2.5-24	3
(11,14)	6-9	6	5	8

According to the LAD based links sorting shown in Table 8, we try to power off the links in that order. Process of routing and powering off according to the LAD based links sorting at the stage of GP is shown from Fig. 4(a) to Fig. 4(j). Finally, the checking results are summarized in Table 9 and for the LAD based links sorting, we get an updated ***Route*** and $G_{+5-5+2+4+5-2-4-5}^{'-v_2-l_{v_{11}v_{14}}}$.

According to the LF based links sorting shown in Table 8, we try to power off the links in that order. First, (0, 3), (4, 7), (7, 9), (3, 6) and (0, 4) in $G_{+5-5}^{'-v_2}$ cannot be powered off, which has been discussed in LAD. Next, we try to power off (6, 9) in $G_{+5-5}^{'-v_2}$, which leads to rerouting for $TD_{1,9}$. By removing (6, 9) and the edges unable to accommodate $TD_{1,9}$, and recovering the corresponding capacity of the nodes and links along {1, 5, 10, 13, 11, 14, 12, 8, 6, 9} in $G_{+5-5}^{'-v_2}$, we get the network graph $G_{+5-5+2}^{'-v_2-l_{v_6v_9}-2}$ shown in Fig. 5(a). The connectivity between node 1 and node 9 has been broken and thus (6, 9) cannot be powered off. Next, we try to power off (8, 12) in $G_{+5-5}^{'-v_2}$, which leads to rerouting for $TD_{1,9}$. By removing (8, 12) and the edges unable to accommodate $TD_{1,9}$, and recovering the corresponding capacity of the nodes and links along {1, 5, 10, 13, 11, 14, 12, 8, 6, 9} in $G_{+5-5}^{'-v_2}$, we get the network graph $G_{+5-5+2}^{'-v_2-l_{v_8v_{12}}-2}$ shown in Fig. 5(b). The connectivity between node 1 and node 9 has been broken and

TABLE 9. Checking for possibility to power off links according to LAD.

Links checked	TDs Impacted	CN?	A new route & QoS	QC
(0,4)	$TD_{0,14}$	×	—	—
	$TD_{4,13}$	—	—	—
(4,7)	$TD_{0,14}$	×	—	—
(0,3)	$TD_{4,13}$	×	—	—
(7,9)	$TD_{0,14}$	×	—	—
(3,6)	$TD_{3,10}$	×	—	—
	$TD_{4,13}$	—	—	—
(11,14)	$TD_{1,9}$	✓	{1,5,10,13,11,8,6,9} (2.5,200,33,0)	✓
	$TD_{4,13}$	✓	{4,0,3,6,8,12,14,13} (2.5,220,33,0)	✓
	$TD_{5,8}$	✓	{5,10,13,14,12,8} (1,155,25,0)	✓
(6,9)	$TD_{1,9}$	×	—	—
(8,12)	$TD_{4,13}$	×	—	—
	$TD_{5,8}$	—	—	—

TABLE 10. Checking for possibility to power off links according to LF.

Links checked	TDs Impacted	CN?	A new route & QoS	QC
(0,3)	Having the identical case to (0,3) in Table 9			
(6,9)	$TD_{1,9}$	×	—	—
(8,12)	$TD_{1,9}$	×	—	—
(4,7)	Having the identical case to (4,7) in Table 9			
(7,9)	Having the identical case to (7,9) in Table 9			
(3,6)	Having the identical case to (3,6) in Table 9			
(0,4)	Having the identical case to (0,4) in Table 9			
(11,14)	Having the identical case to (11,14) in Table 9			

thus (8, 12) cannot be powered off. Lastly, (11, 14) can be powered off in $G'^{-v_2}_{+5-5}$ as discussed in LAD, thus we obtain $G'^{-v_2-l_{v_{11}v_{14}}}_{+5-5+2+4+5-2-4-5}$. Finally, the checking results are summarized in Table 10. Hence, for the LF based links sorting, we get the same ***Route*** and $G'^{-v_2-l_{v_{11}v_{14}}}_{+5-5+2+4+5-2-4-5}$ as that of the LAD based links sorting.

In the stage of GP, we succeed in powering off node 2 and its adjacent links, (0, 2) and (2, 5) in the first round of iteration according to the nodes sorting of LD and LF, and powering off (11, 14) in the second round of iteration according to the LAD/LF based links sorting. We update $\boldsymbol{Route}_{1,9}$, $\boldsymbol{Route}_{4,13}$ and $\boldsymbol{Route}_{5,8}$ in the ***Route*** and get a smaller network sub-graph $G'' \leftarrow G'^{-v_2-l_{v_{11}v_{14}}}_{+5-5+2+4+5-2-4-5}$.

3) FEASIBLE CHECKING STAGE FOR ROUTING (FC)

We devise the stage so as to try to make the network sub-graph obtained above further be reduced. FC is a stage similar to ACNN except that it routes all the traffic demands based on the sub-graph G'' obtained by two rounds of operations in ACNN and GP, which is different from the original network graph G based routing in ACNN. The network sub-graph obtained in the stage is marked as G'''.

Following the above example, we reroute all the traffic demands: $TD_{0,14}$, $TD_{1,9}$, $TD_{3,10}$, $TD_{4,13}$ and $TD_{5,8}$. After recovering the corresponding capacity of the nodes and links along $\boldsymbol{Route}_{0,14}$, $\boldsymbol{Route}_{1,9}$, $\boldsymbol{Route}_{3,10}$, $\boldsymbol{Route}_{4,13}$, and $\boldsymbol{Route}_{5,8}$ in G'' and removing (6, 9) provisionally only when routing $TD_{0,14}$ due to its AC smaller than $TD_{0,14}$, we get the sub-graph $G''^{-1}_{1+2+3+4+5}$ shown in Fig. 6(a). Because of the limitation to paper pages, we give the result for routing each demand directly instead of the detailed solving process as that in the ACNN. $TD_{0,14}$, $TD_{1,9}$, $TD_{3,10}$, $TD_{4,13}$ and $TD_{5,8}$ are routed along $\boldsymbol{Route}_{0,14} \leftarrow \{0, 4, 7, 9, 12, 14\}$ with $QoS_{0,14} \leftarrow (4, 205, 31, 0)$, $\boldsymbol{Route}_{1,9} \leftarrow \{1, 5, 10, 13, 11, 8, 6, 9\}$ with $QoS_{1,9} \leftarrow (2.5, 200, 33, 0)$, $\boldsymbol{Route}_{3,10} \leftarrow \{3, 6, 8, 12, 14, 13, 10\}$ with $QoS_{3,10} \leftarrow (2.5, 180, 28, 0)$, $\boldsymbol{Route}_{4,13} \leftarrow \{4, 0, 3, 6, 8, 11, 13\}$ with $QoS_{4,13} \leftarrow (2.5, 175, 28, 0)$ and $\boldsymbol{Route}_{5,8} \leftarrow \{5, 10, 13, 11, 8\}$ with $QoS_{5,8} \leftarrow (1, 110, 20, 0)$ respectively, shown in Figs. 6(b-f). Therefore, we update the routes in ***Route***and get the network sub-graph: $G''' \leftarrow G''_{+1+2+3+4+5-1-2-3-4-5}$.

4) GREEDY CHECKING STAGE FOR PRUNING (GC)

GC is a stage similar to GP. The differences between GP and GC is that the former carries out a further switching-off operation based on the sub-graph G' obtained in ACNN, while the latter lies in carrying out an indispensable check procedure to verify whether the sub-graph G''' obtained in FC is a minimum set of network elements powered on to enable to route all the current traffic demands. The network sub-graph obtained in the stage is marked as $G^{(4)}$.

Following the above example, based on G''' and ***Route*** obtained in the stage of FC, we check whether nodes can be powered off or not first, and then links are checked in a secondary round of iteration. Because of the limitation to paper pages, we give the brief description for checking each demand directly instead of the detailed step-by-step solving process as that in the GP. We first consider the nodes sorting. We sort the remainder nodes except for the source nodes and the destination nodes of all the traffic demands according to the criteria of LD and LF, shown in Table 11.

According to the LD based nodes sorting shown in Table 11, we verify whether the nodes can be powered off in the order of 7, 11, 12 and 6. We first check the possibility to power off node 7. It will lead to rerouting for $TD_{0,14}$ if

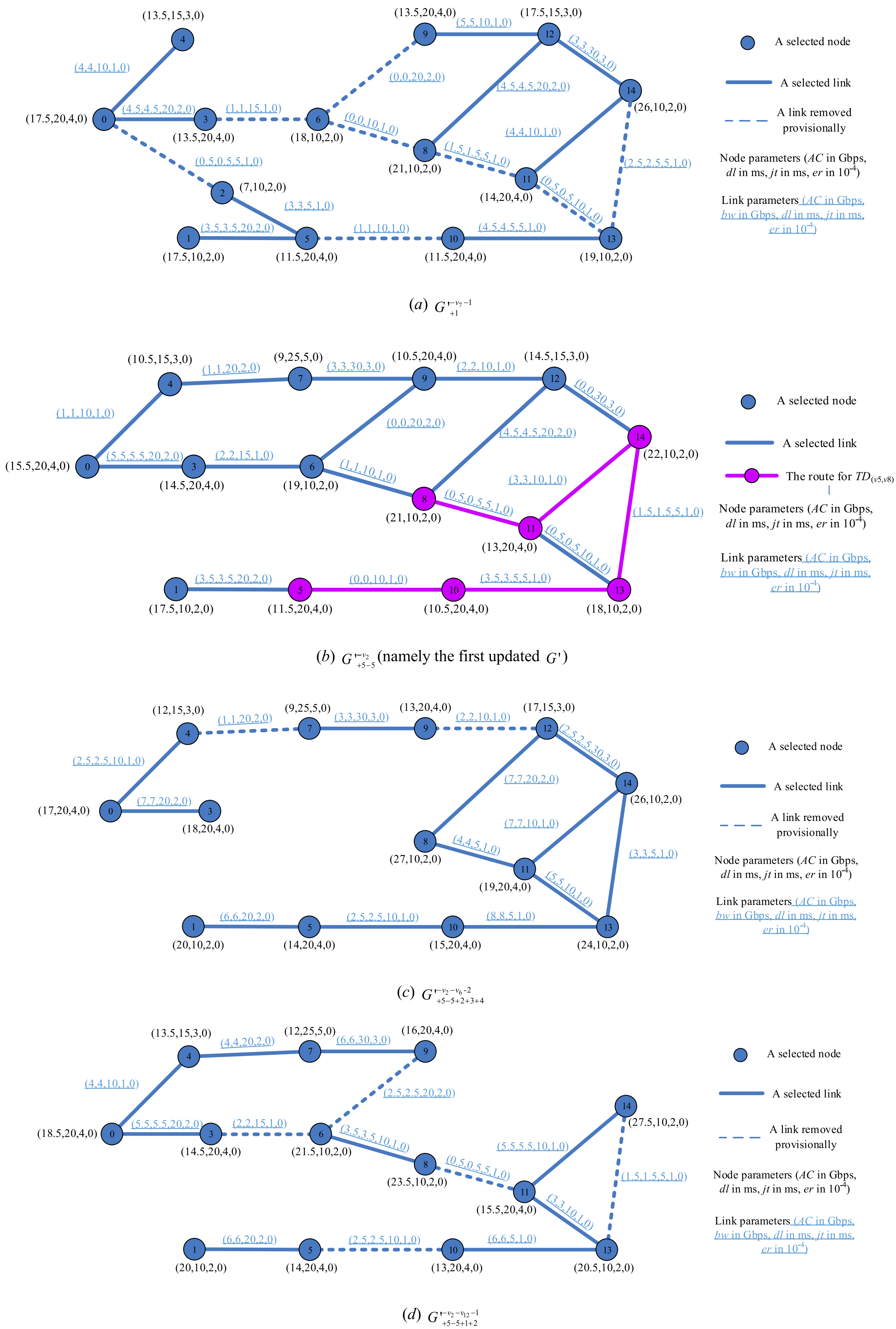
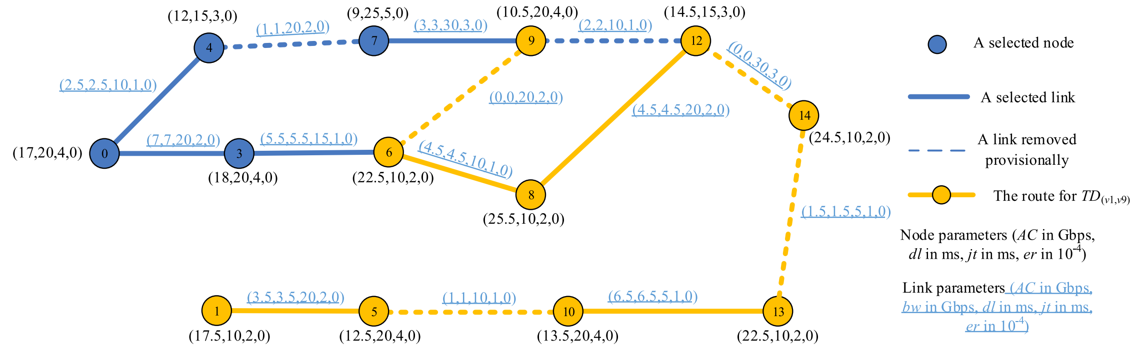
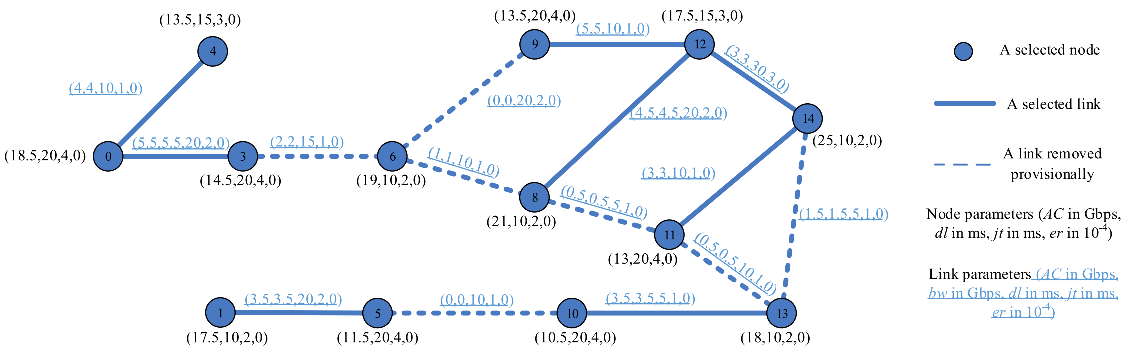


FIGURE 3. Process of routing and powering off according to the LD/LF based nodes sorting at the stage of GP.



(e) $G^{\prime-v_2-v_{11}-2-3}_{+5-5+2+3+4+5-2}$



(f) $G^{\prime-v_2-v_7-1}_{+5-5+1}$

FIGURE 3. *(Continued.)* **Process of routing and powering off according to the LD/LF based nodes sorting at the stage of GP.**

TABLE 11. LD/LF based nodes sorting over G'''.

Nodes	D-SD-OC	LD Sorting	Flow-SF	LF Sorting
6	3-8-6	4	12	4
7	2-5	1	6	1
11	2-6	2	10-25.5	2
12	3-8-5	3	10-28.5	3

TABLE 12. LAD/LF based link sorting over G'''.

Links	AD-SAD-AOC	LAD Sorting	Flow-AF	LF Sorting
(0,3)	4-5-4	3	1.5	1
(0,4)	4-4	1	4.5	7
(3,6)	5-8-4.75	5	3.5	6
(4,7)	4-5-3.75	2	3-13.5	4
(6,9)	6-10-5.75	6	2.5	3
(7,9)	5-8-4.25	4	3-14.5	5
(8,12)	6-10-6	7	2	2

node 7 is powered off. Owing to the remainder capacity "2" of (3, 6) unable to accommodate $TD_{0,14}$, so node 7 cannot be powered off. Next, It will lead to rerouting for $TD_{1,9}$, $TD_{4,13}$ and $TD_{5,8}$ if node 11 is powered off. Owing to the remainder capacity "0.5" of (12, 14) unable to accommodate them, so node 11 cannot be powered off. Next, we check the possibility to power off node 12. It will lead to rerouting for $TD_{0,14}$ and $TD_{3,10}$ if node 12 is powered off. Owing to no more capacity in (8, 11) able to accommodate them, so node 12 cannot be powered off. Finally, It will lead to rerouting for $TD_{1,9}$, $TD_{3,10}$ and $TD_{4,13}$ if node 6 is powered off. Owing to the remainder capacity "1" of (4, 7) unable to accommodate $TD_{3,10}$ and $TD_{4,13}$, so node 6 cannot be powered off. So for the LD based nodes sorting, none of node 7, node 11, node 12 and node 6 can be powered off. In this case, it is really unnecessary to check the nodes again according to the LF based nodes sorting.

Next we check whether the links in G''' can be powered off or not. Still, none of the sole links ((1, 5), (5, 10) and (10, 13)) connecting the source nodes or the destination nodes of all the traffic demands and three pairs of links, (13, 14) and (11, 13), (6, 8) and (9, 12), and (12, 14) and (8, 11), can be powered off. Now, we sort the remainder links according to the criteria of LAD and LF, shown in Table 12.

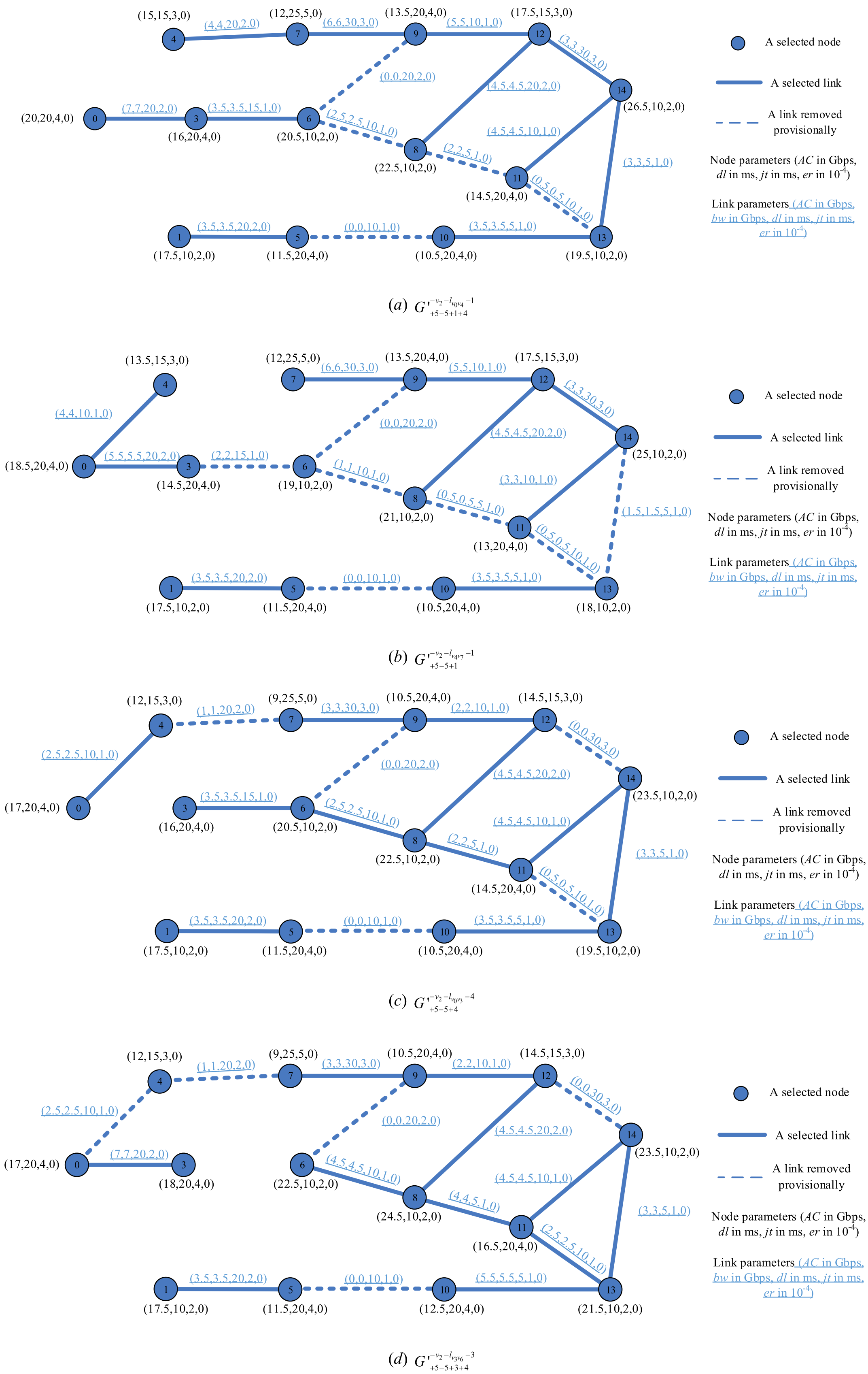


FIGURE 4. Process of routing and powering off according to the LAD based links sorting at the stage of GP.

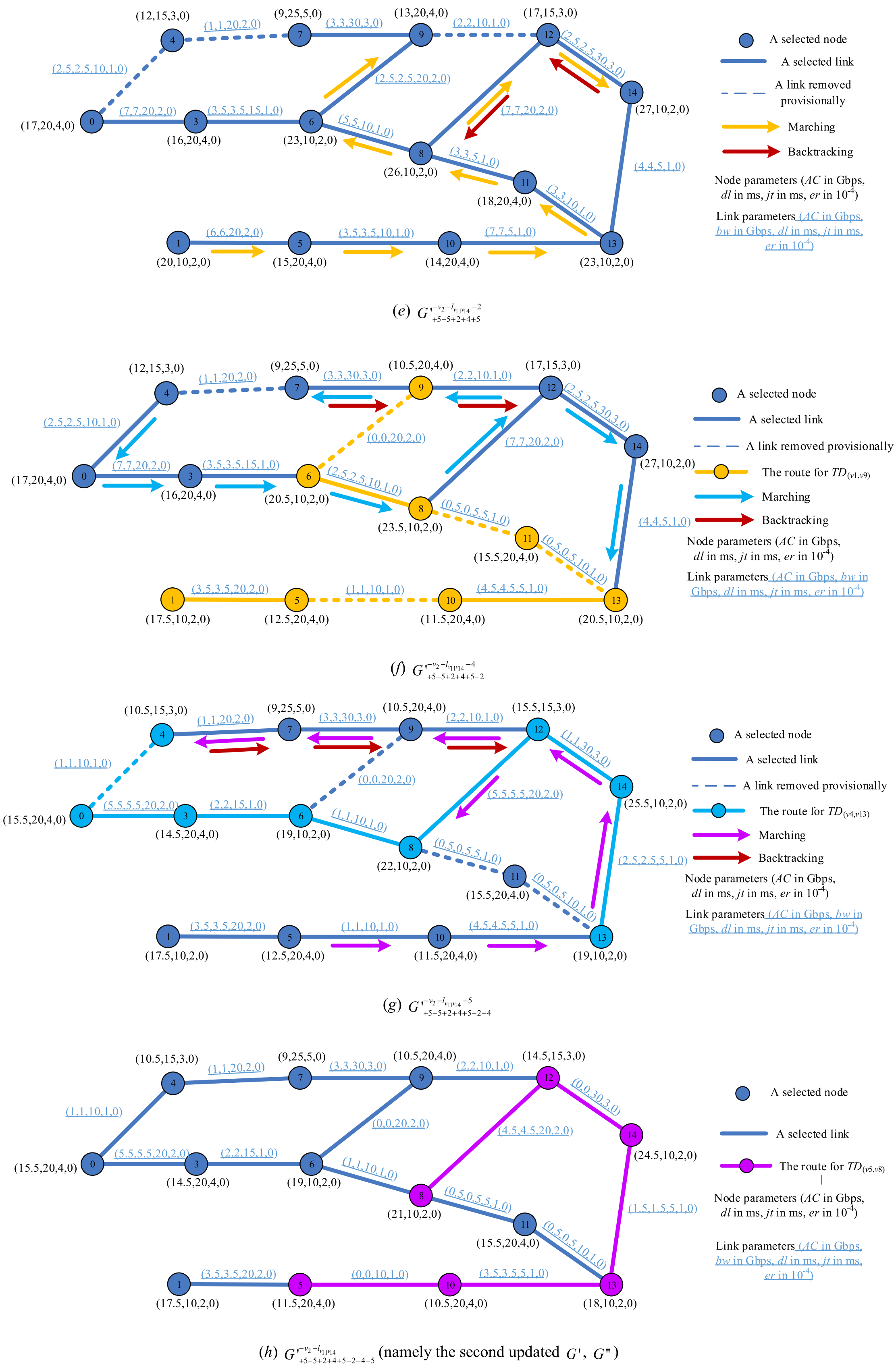
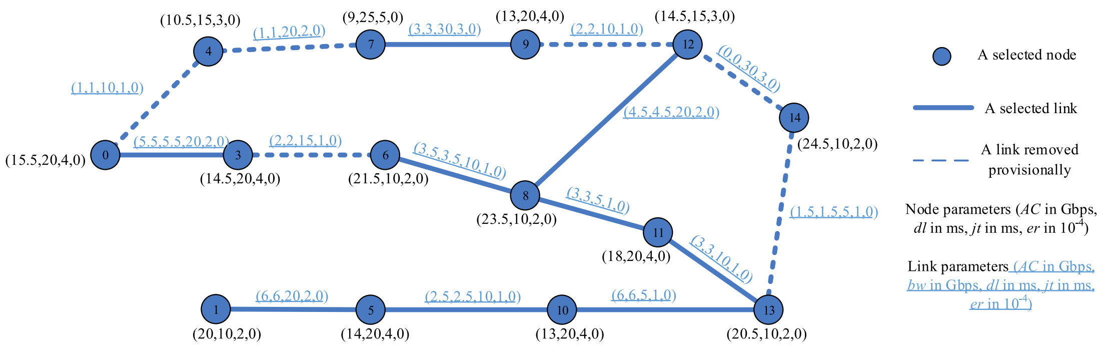
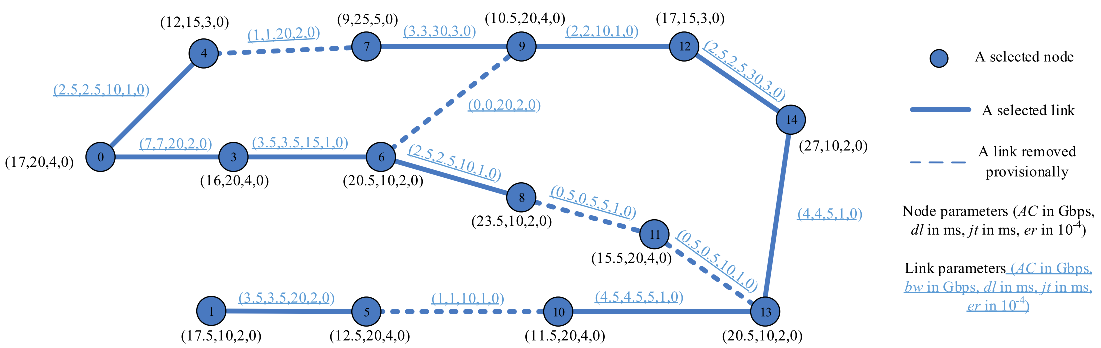


FIGURE 4. *(Continued.)* **Process of routing and powering off according to the LAD based links sorting at the stage of GP.**



(i) $G'^{-v_2-l_{v_{11}v_{14}}-l_{v_6v_9}-2}_{+5-5+2+4+5-2-4-5+2}$



(j) $G'^{-v_2-l_{v_{11}v_{14}}-l_{v_8v_{12}}-4}_{+5-5+2+4+5-2-4-5+4+5}$

FIGURE 4. ***(Continued.)*** **Process of routing and powering off according to the LAD based links sorting at the stage of GP.**

According to the LAD based links sorting shown in Table 12, we verify whether the links can be powered off in that order. First, we check the possibility to power off $(0, 4)$. It will lead to rerouting for $TD_{0,14}$ and $TD_{4,13}$ if $(0, 4)$ is powered off. Owing to the remainder capacity "2.5" of $(6, 8)$ unable to accommodate $TD_{0,14}$, so $(0, 4)$ cannot be powered off. Next, It will lead to rerouting for $TD_{0,14}$ if $(4, 7)$ or $(7, 9)$ is powered off. Owing to the remainder capacity "2" of $(3, 6)$ unable to accommodate $TD_{0,14}$, so neither $(4, 7)$ nor $(7, 9)$ can be powered off. Next, It will lead to rerouting for $TD_{4,13}$ if $(0, 3)$ is powered off. Owing to the remainder capacity "1" of $(4, 7)$ unable to accommodate $TD_{4,13}$, so $(0, 3)$ cannot be powered off. Next, It will lead to rerouting for $TD_{3,10}$ and $TD_{4,13}$ if $(3, 6)$ is powered off. Owing to the remainder capacity "1" of $(4, 7)$ unable to accommodate $TD_{3,10}$ and $TD_{4,13}$, so $(3, 6)$ cannot be powered off. Next, It will lead to rerouting for $TD_{1,9}$ if $(6, 9)$ is powered off. Owing to no enough capacity (size of "1" and "2", respectively) in $(4, 7)$ or $(9, 12)$ able to accommodate $TD_{1,9}$, so $(6, 9)$ cannot be powered off. Finally, It will lead to rerouting for $TD_{3,10}$ if $(8, 12)$ is powered off. Owing to no enough capacity (size of "1", "0" and "0", respectively) in $(4, 7)$, $(6, 9)$ or $(8, 11)$ able to accommodate $TD_{3,10}$, so $(8, 12)$ cannot be powered off. So for the LAD based links sorting, none of $(0, 4)$, $(4, 7)$, $(0, 3)$, $(7, 9)$, $(3, 6)$, $(6, 9)$ and $(8, 12)$ can be powered off. In this case, it is really unnecessary to check the links again according to the LF based links sorting.

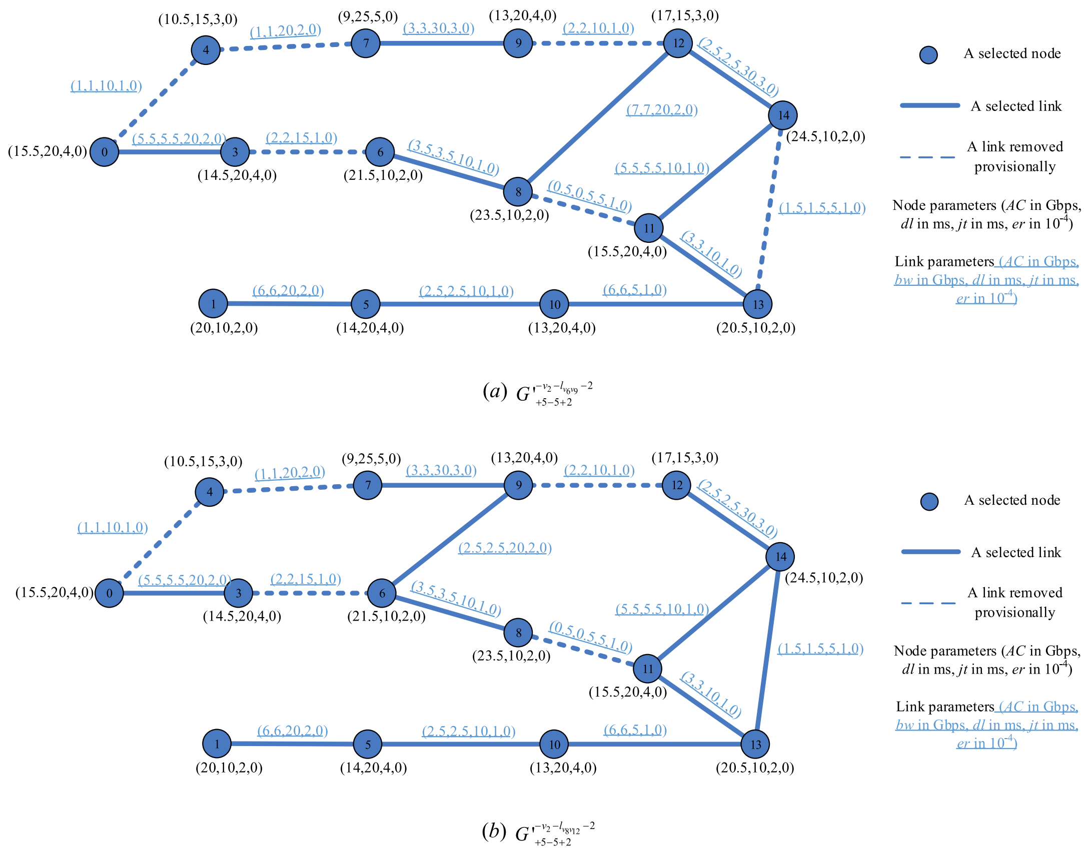
By the above checking, in the example, we conclude that no any nodes or links can be powered off in G''', namely $G^{(4)} \leftarrow G'''$, and there is no change to the routes in ***Route***.

C. TRAFFIC ASSIGNMENT STAGE INSIDE THE BUNDLED LINKS (TAB)

Based on the network graph and the routing solution obtained from the stage of GGR, we try to achieve a further energy saving by investigating how to assign traffic flowing through a link reasonably among the cables in the stage.

Specifically, for $n_{(i,j)} \le N_{(i,j)}$ cables of $(i, j) \in E$, whose available capacities are $AC^1_{(i,j)}, AC^2_{(i,j)}, \ldots, AC^{n_{(i,j)}}_{(i,j)}$ respectively, we aim to seek a traffic assignment solution $\boldsymbol{Sol}_{(i,j)}$ among the cables to accommodate traffic demands carried on them and make power consumption minimum for each link (i, j).

We assume that the set of traffic demands $TD_{s,d} \in D$ flowing through the link $(i, j) \in E$ is denoted as $\boldsymbol{TDS}_{(i,j)}$. The set of the active cables in (i, j) is denoted as $\boldsymbol{CBS}^{\text{active}}_{(i,j)} = \left\{(i,j)^{\text{active}}_1, (i,j)^{\text{active}}_2, \ldots, (i,j)^{\text{active}}_{a_{(i,j)}}\right\}$ and the set of the sleeping cables in (i, j) is denoted as $\boldsymbol{CBS}^{\text{sleeping}}_{(i,j)} = \left\{(i,j)^{\text{sleeping}}_1, (i,j)^{\text{sleeping}}_2, \ldots, (i,j)^{\text{sleeping}}_{s_{(i,j)}}\right\}$.



(a) $G^{\Gamma^{-v_2-l_{6,9}}-2}_{+5-5+2}$

(b) $G^{\Gamma^{-v_2-l_{9,12}}-2}_{+5-5+2}$

FIGURE 5. Process of routing and powering off according to the LF based links sorting at the stage of GP.

Obviously, $a_{(i,j)} + s_{(i,j)} = N_{(i,j)}$. We mark the solving set of allocating $TD^{s,d}_{(i,j)}$ among cables in (i, j) as $\boldsymbol{CBS}\left(TD^{s,d}_{(i,j)}\right)$.

As for the traffic assignment problem in GRB2_UB, we adopt TAB_LU described as follows to solve it. Lines 2-5 assign the traffic demands in $\boldsymbol{TDS}_{(i,j)}$ among the cables in $\boldsymbol{CBS}^{\text{active}}_{(i,j)}$ randomly. Following the above example, the assignment results among all the cables of each link are shown at the first column of each cable in Table 13.

As for the traffic assignment problem in GRB2_IB, we adopt TAB_LI described as follows to solve it. Lines 4-6 continuously awaken the cable with the maximum capacity in $\boldsymbol{CBS}^{\text{sleeping}}_{(i,j)}$ to reduce the gap $\left|\Delta_{(i,j)}\right|$. Line 7 awakens the cable which has the minimum capacity beyond the remaining gap. Lines 9-11 continuously put the cable with the minimum capacity in $\boldsymbol{CBS}^{\text{active}}_{(i,j)}$ into sleep if powering off any cable in $\boldsymbol{CBS}^{\text{active}}_{(i,j)}$ can still accommodate the traffic demands in $\boldsymbol{TDS}_{(i,j)}$. Lines 14-17 assign the traffic demands in $\boldsymbol{TDS}_{(i,j)}$ among the cables in $\boldsymbol{CBS}^{\text{active}}_{(i,j)}$ randomly. Following the above example, to be more general, we focus on $(6, 8)$ whose capacity size is 7. $\boldsymbol{TDS}_{(6,8)} = \left\{TD_{1,9}, TD_{3,10}, TD_{4,13}\right\}$, $\boldsymbol{CBS}^{\text{active}}_{(6,8)} = \left\{(6,8)_1, (6,8)_2, (6,8)_3\right\}$, $C_{\boldsymbol{CBS}^{\text{active}}_{(6,8)}} = 5 < Size\left(\boldsymbol{TDS}_{(6,8)}\right) = 6$, $\left|\Delta_{(6,8)}\right| = 1$, $\boldsymbol{CBS}^{\text{sleeping}}_{(6,8)} = \left\{(6,8)_4, (6,8)_5, (6,8)_6\right\}$, so we awaken $(6, 8)_4$ which makes $\left(C_{(6,8)_k \in \boldsymbol{CBS}^{\text{sleeping}}_{(6,8)}} - \left|\Delta_{(6,8)}\right|\right)$ get the minimum value "0". We assign $TD_{1,9}$, $TD_{3,10}$ and $TD_{4,13}$ among the active cables in $(6, 8)$ randomly, and get a solution of $\boldsymbol{Sol}(TD^{1,9}_{(6,8)}) = \left\{\left((6,8)_1, TD_{1,9}(2)\right), \left((6,8)_2, TD_{1,9}(0.5)\right)\right\}$, $\boldsymbol{Sol}(TD^{3,10}_{(6,8)}) = \left\{\left((6,8)_2, TD_{3,10}(1)\right), \left((6,8)_3, TD_{3,10}(1)\right)\right\}$, $\boldsymbol{Sol}(TD^{4,13}_{(6,8)}) = \left\{\left((6,8)_3, TD_{4,13}(0.5)\right), \left((6,8)_4, TD_{4,13}(1)\right)\right\}$, $\boldsymbol{Sol}\left(\boldsymbol{TDS}_{(6,8)}\right) = \boldsymbol{Sol}\left(TD^{1,9}_{(6,8)}\right) \cup \boldsymbol{Sol}\left(TD^{3,10}_{(6,8)}\right) \cup \boldsymbol{Sol}\left(TD^{4,13}_{(6,8)}\right)$. The assignment solutions to the traffic demands in other links can be obtained in a similar way, so we give the results directly at the second column of each cable in Table 13.

V. SIMULATION

We select the Hop-by-hop Distributed Energy-Efficient Routing scheme (HDEER) devised in [33], the Single Shortest Path First (SSPF) heuristics proposed in [3] and the Multiple paths by Shortest Path First-link first (MSPF) heuristics proposed in [34] as the benchmarks.

HDEER is a two-stage routing scheme where the distributed loop-free multi-path finding Algorithm (D_LoopFree or D_LoopFree-TA) is firstly performed to guarantee loop-free routing, and then the optimal distributed routing algorithm (D_Routing-S or D_Routing-D) is executed for energy-efficient routing in each node to guide the traffic distribution among the multiple loop-free paths. Since only devised originally over the non-bundled-link scenario,

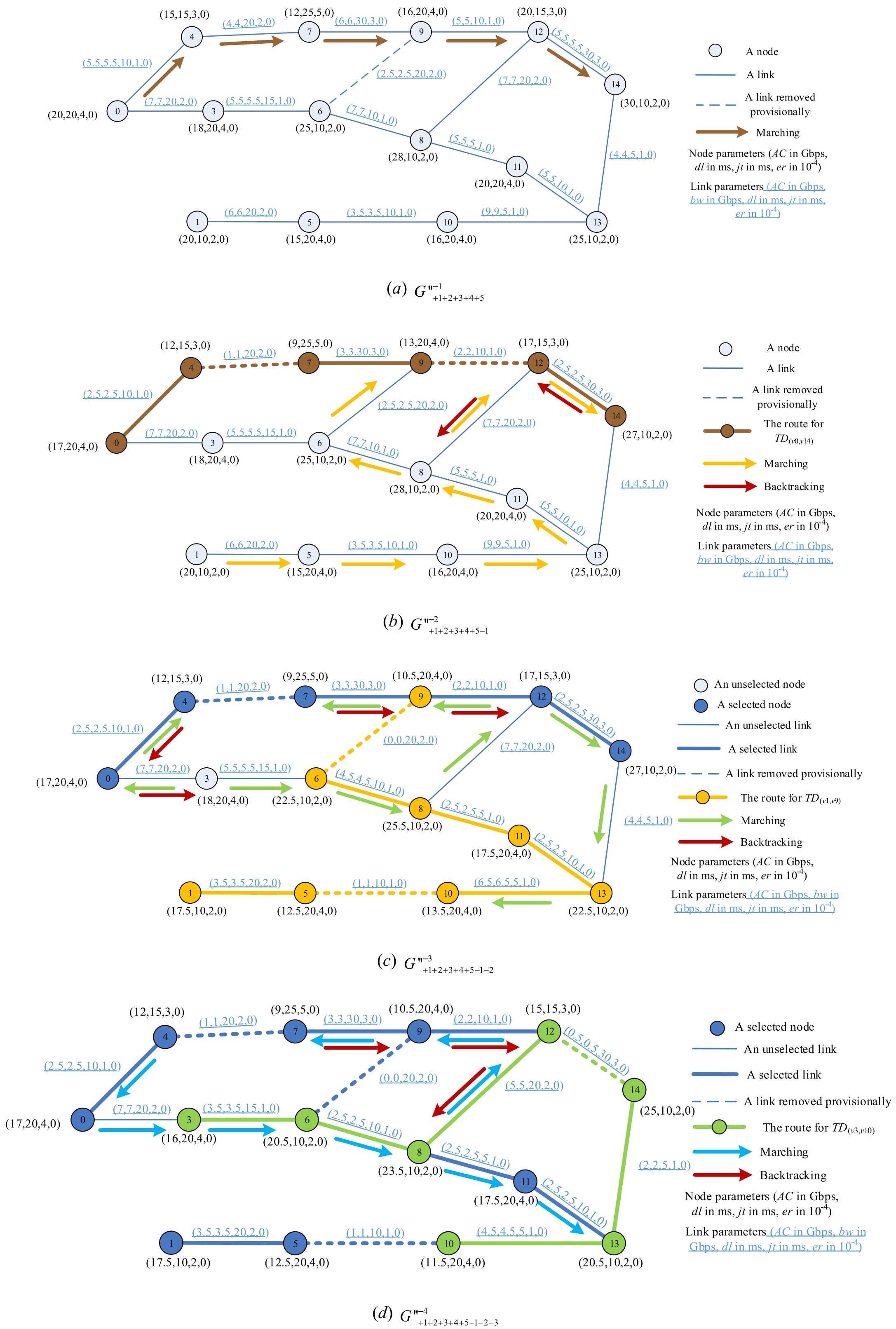
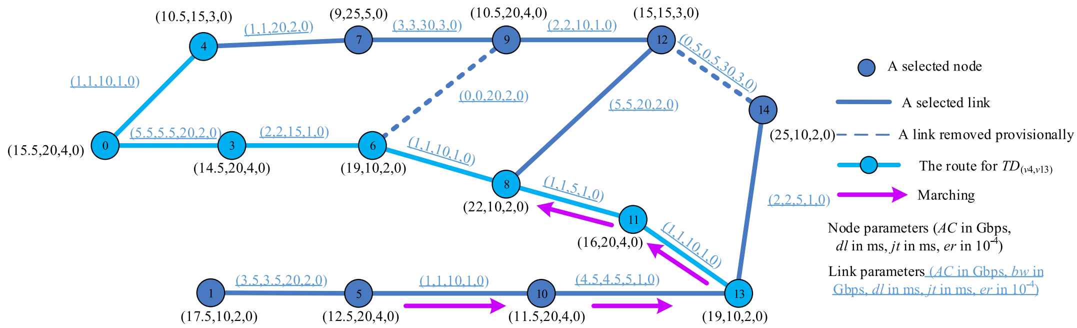
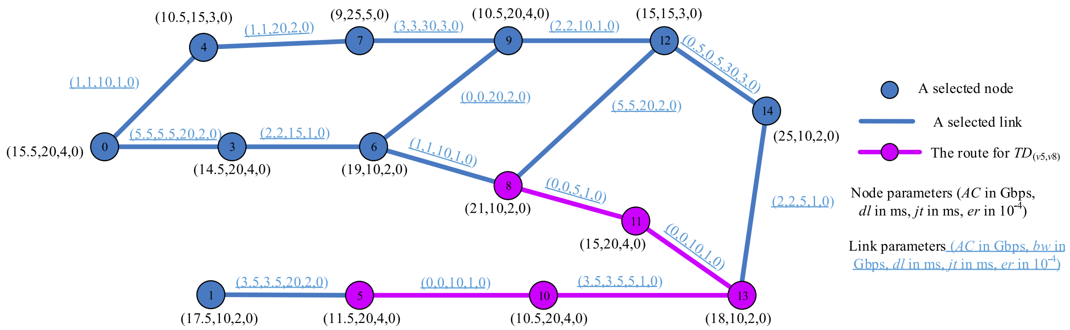


FIGURE 6. **Process of routing and powering off at the stage of FC.**



(e) $G'''^{-5}_{+1+2+3+4+5-1-2-3-4}$



(f) $G''_{+1+2+3+4+5-1-2-3-4-5}(G''')$

FIGURE 6. ***(Continued.)*** **Process of routing and powering off at the stage of FC.**

Function *assign* $\left(TD^{s,d}_{(i,j)}, (i,j)\right)$

Assign $TD^{s,d}_{(i,j)}$ among the active cables in (i,j) randomly and obtain $\boldsymbol{CBS}\left(TD^{s,d}_{(i,j)}\right)$;
Subtract the corresponding size $TD^{s,d}_{(i,j)_k}$ occupied by $TD^{s,d}_{(i,j)}$ from the AC of each cable $(i,j)_k$ in $\boldsymbol{CBS}\left(TD^{s,d}_{(i,j)}\right)$;
$\boldsymbol{Sol}\left(TD^{s,d}_{(i,j)}\right) \leftarrow \left\{\left((i,j)_k, TD_{s,d}\left(TD^{s,d}_{(i,j)_k}\right)\right) \middle| (i,j)_k \in \boldsymbol{CBS}\left(TD^{s,d}_{(i,j)}\right)\right\}$;
Return $\boldsymbol{Sol}\left(TD^{s,d}_{(i,j)}\right)$.

Algorithm TAB_LU

Input: $G^{(n)}$, D, $\boldsymbol{TDS}_{(i,j)}$, ***Route***
Output: ***Sol***

```
For each (i, j) in G^(n) do
    For TD^{s,d}_{(i,j)} ∈ TDS_{(i,j)} do
        assign (TD^{s,d}_{(i,j)}, (i, j));
        Sol (TDS_{(i,j)}) ← Sol (TDS_{(i,j)})
            ∪Sol (TD^{s,d}_{(i,j)});
    End For
    Sol ← Sol ∪ Sol (TDS_{(i,j)});
End For
Return Sol.
```

HDEER has to be modified to an enhanced bundled-link version so that it will be appropriate to be compared with ours. So we add a third stage to HDEER so as to perform traffic assignment among the cables in a bundled link and assume that traffic flow is always iteratively assigned to the cable with the smallest gap between the flow size and its current AC.

SSPF firstly uses each shortest path computed via *Dijkstra*'s algorithm to route the traffic flow of each demand; then, it calculates the total number of cables for each link needed to route all demands in order to switch off the maximal number of unused cables from each link at the same time ensure that the remaining cables are capable of meeting all traffic demands; next, it iteratively selects a candidate link and aims to switch off one of its cables by a function used in SSPF-2 to select the link with the smallest average flow per demand, and for each selected link, a greedy heuristic is used to check if deleting a cable is feasible; finally, it carries out a sequential process of restoring the deleted cables in SSPF-R, repeatedly assuming that a deleted cable leads to a local minimum and

TABLE 13. TAB_LU/TAB_LI.

(i,j)	TD in (i,j)	$(i,j)_1$		$(i,j)_2$		$(i,j)_3$		$(i,j)_4$		$(i,j)_5$		$(i,j)_6$	
		OC	OC/OFF	OC	OC/OFF	OC	OC/OFF	OC	OC/OFF	OC	OC/OFF	OC	OC/OFF
(0,3)	$TD_{4,13}$	1.5	1.5	0	OFF	0	OFF	0	OFF	0	OFF	0	OFF
(0,4)	$TD_{0,14}$	2	2	1	1	0	0	0	OFF	0	OFF	—	—
	$TD_{4,13}$	0	0	0.5	0.5	1	1	0	OFF	0	OFF	—	—
(1,5)	$TD_{1,9}$	2	2	0.5	0.5	0	OFF	0	OFF	0	OFF	—	—
(3,6)	$TD_{3,10}$	2	2	0	0	0	OFF	0	OFF	0	OFF	—	—
	$TD_{4,13}$	0	0	1.5	1.5	0	OFF	0	OFF	0	OFF	—	—
(4,7)	$TD_{0,14}$	1.5	1.5	1	1	0.5	OFF	0	0.5	—	—	—	—
(5,10)	$TD_{1,9}$	2	2	0.5	0.5	0	0	—	—	—	—	—	—
	$TD_{5,8}$	0	0	0.5	0.5	0.5	0.5	—	—	—	—	—	—
(6,8)	$TD_{1,9}$	2	2	0.5	0.5	0	0	0	0	0	OFF	0	OFF
	$TD_{3,10}$	0	0	1	1	1	1	0	0	0	OFF	0	OFF
	$TD_{4,13}$	0	0	0	0	0.5	0.5	1	1	0	OFF	0	OFF
(6,9)	$TD_{1,9}$	1	1	1	1	0.5	0.5	—	—	—	—	—	—
(7,9)	$TD_{0,14}$	2	2	1	1	0	OFF	0	OFF	0	OFF	—	—
(8,11)	$TD_{1,9}$	2	2	0.5	0.5	0	0	0	0	—	—	—	—
	$TD_{4,13}$	0	0	1	1	0.5	0.5	0	0	—	—	—	—
	$TD_{5,8}$	0	0	0	0	0.5	0.5	0.5	0.5	—	—	—	—
(8,12)	$TD_{3,10}$	2	2	0	OFF	0	OFF	0	OFF	0	OFF	0	OFF
(9,12)	$TD_{0,14}$	2	2	1	1	0	OFF	0	OFF	—	—	—	—
(10,13)	$TD_{1,9}$	2	2	0.5	0.5	0	0	0	OFF	0	OFF	0	OFF
	$TD_{3,10}$	0	0	1.5	1.5	0.5	0.5	0	OFF	0	OFF	0	OFF
	$TD_{5,8}$	0	0	0	0	1	1	0	OFF	0	OFF	0	OFF
(11,13)	$TD_{1,9}$	2	2	0.5	0.5	0	0	0	0	—	—	—	—
	$TD_{4,13}$	0	0	1	1	0.5	0.5	0	0	—	—	—	—
	$TD_{5,8}$	0	0	0	0	0.5	0.5	0.5	0.5	—	—	—	—
(12,14)	$TD_{0,14}$	2	2	1	1	0	0	0	0	0	OFF	—	—
	$TD_{3,10}$	0	0	0.5	0.5	1	1	0.5	0.5	0	OFF	—	—
(13,14)	$TD_{3,10}$	1.5	1.5	0.5	OFF	0	OFF	0	0.5	—	—	—	—

the remaining deleted cables are correct decisions to correct the possible mistakes which lead to the local minima.

MSPF firstly generates k shortest paths via *Yen*'s algorithm [35] for each traffic demand; then distributes the traffic flow in each demand starting from the shortest candidate path until the total flow is routed; thus calculates the remaining capacity and the maximum number of redundant cables to power off for each bundled link; and finally a checking process repeatedly selects the cable whose link has the largest remaining capacity to determine whether it can be powered off while guaranteeing the affected flows can still be rerouted successfully.

A. DEVELOPMENT ENVIRONMENT

We perform our simulation under the integrated development environment of Microsoft Visual Studio 2010 based on the OS of Windows 8.1 professional 64bit with the CPU of Intel Quad-Core i5-4590 @ 3.30GHz and the RAM of 4GB (DDR3, 1600MHz).

B. NETWORK TOPOLOGIES

We perform comprehensive experiments on four real backbone network topologies, that is, CERNET2 (the China Education and Research NETwork 2) available in [36], CANARIE (CAnadian Network for the Advancement of Research, Industry, and Education) available in [37], GéANT available in [38] and INTERNET2 available in [39]. The characteristics of the four network topologies are summarized in Table 14.

C. MATHEMATICAL FORMULATION OF TASK OFFLOADING MODEL

Although traffic in the backbone network changes with time and even sometime has an uncertain burst, it actually follows

Algorithm TAB_LI

Input: $G^{(n)}$, D, $\boldsymbol{TDS}_{(i,j)}$, $\boldsymbol{CBS}^{\text{active}}_{(i,j)}$, $\boldsymbol{CBS}^{\text{sleeping}}_{(i,j)}$, $\boldsymbol{Route}$
Output: $\boldsymbol{Sol}$

For each (i,j) in $G^{(n)}$ **do**
  $\Delta_{(i,j)} \leftarrow \left(C_{\boldsymbol{CBS}^{\text{active}}_{(i,j)}} - Size\left(\boldsymbol{TDS}_{(i,j)}\right)\right)$;
  If $\Delta_{(i,j)} < 0$ **then**
    While $\left|\Delta_{(i,j)}\right| > \max\left(C_{(i,j)_k \in \boldsymbol{CBS}^{\text{sleeping}}_{(i,j)}}\right)$ **do**
      Remove the cable $(i,j)^{C_{\max}}$ with $\max\left(C_{(i,j)_k \in \boldsymbol{CBS}^{\text{sleeping}}_{(i,j)}}\right)$ from $\boldsymbol{CBS}^{\text{sleeping}}_{(i,j)}$ and add it to $\boldsymbol{CBS}^{\text{active}}_{(i,j)}$;
    End While
    Remove the cable $(i,j)^{\left(C-\left|\Delta_{(i,j)}\right|\right)_{\min}}$ with $\min\left(\left(C_{(i,j)_k \in \boldsymbol{CBS}^{\text{sleeping}}_{(i,j)}} - \left|\Delta_{(i,j)}\right|\right) \geq 0\right)$ from $\boldsymbol{CBS}^{\text{sleeping}}_{(i,j)}$ and add it to $\boldsymbol{CBS}^{\text{active}}_{(i,j)}$;
  Else If $\Delta_{(i,j)} > 0$ **then**
    While $\Delta_{(i,j)} \geq \min\left(C_{(i,j)_k \in \boldsymbol{CBS}^{\text{active}}_{(i,j)}}\right)$ **do**
      Remove the cable $(i,j)^{C_{\min}}$ with $\min\left(C_{(i,j)_k \in \boldsymbol{CBS}^{\text{active}}_{(i,j)}}\right)$ from $\boldsymbol{CBS}^{\text{active}}_{(i,j)}$ and add it to $\boldsymbol{CBS}^{\text{sleeping}}_{(i,j)}$;
    End While
  End If
  End If
  For $TD^{s,d}_{(i,j)} \in \boldsymbol{TDS}_{(i,j)}$ **do**
    $assign\left(TD^{s,d}_{(i,j)}, (i,j)\right)$;
    $\boldsymbol{Sol}\left(\boldsymbol{TDS}_{(i,j)}\right) \leftarrow \boldsymbol{Sol}\left(\boldsymbol{TDS}_{(i,j)}\right) \cup \boldsymbol{Sol}\left(TD^{s,d}_{(i,j)}\right)$;
  End For
  $\boldsymbol{Sol} \leftarrow \boldsymbol{Sol} \cup \boldsymbol{Sol}\left(\boldsymbol{TDS}_{(i,j)}\right)$;
End For
Return $\boldsymbol{Sol}$.

TABLE 14. Characteristics of topologies under consideration.

Topologies	#Nodes	#Links <10Gbps	#Links [10Gbps, 100Gbps)	#Links ⩾100Gbps
CERNET2	20	18/22	4/22	0/22
CANARIE	31	0/39	0/39	39/39
GéANT	45	14/73	30/73	29/73
INTERNET2	64	0/78	0/78	78/78

a well-known daily and weekly discipline [40]. Further, traffic matrices can generally be estimated with good accuracy through statistical analysis and mathematical derivation, and allow planning network resources allocated in advance with limited uncertainty margins [41]. Considering that statistical inference approaches can usually provide more reliable estimates for the traffic matrices than the deterministic ones owing to using more complete traffic data throughout a long time, we make use of the statistical methodology proposed in our previous work [42] to obtain the estimated traffic matrices as the input of our proposed routing and planning problems.

For CERNET2, we use a traffic dataset on links provided by the Aladdin network management information platform available in [43]. For CANARIE, GéANT and INTERNET2, we use the traffic profiles on links provided by a library of test instances for Survivable fixed telecommunication Network Design (SNDlib) available in [44].

In our simulation, similar to [45], we acquire our traffic profiles on links by computing a mean value every 5 mins within different time periods of a day during a successive duration of 5 months from March 1st, 2016 to July 31st, 2016. Also according to the traffic profiles of these academic and research backbone networks, we split a day into six time periods including PPs (Peak Periods) (9:00-11:00, 14:00-16:00 and 19:00-23:00) and OPPs (Off-Peak Periods) (23:00-9:00, 11:00-14:00 and 16:00-19:00) and then estimate traffic matrices for each period.

D. NETWORK DEPLOYMENT AND RELATED PARAMETERS SETTING

Each node is assumed to have the same type of core router with the available maximum number of 4 LCs per CHA and the available maximum number of 4 ports per LC, and the number of CHAs configured in a node is set according to the necessary requirements for networking. A series of deployment and configuration schemes over different network topologies are shown in Table 15. Moreover, the Bundled Sizes (BSs) of links range from 2 to 10 and the number of ILAs and REGs in a cable is calculated according to [46].

By referring to Cisco XR 12000 Series and Cisco 12000 Series Routers [47], the settings of power consumption parameters used in the simulation are shown in Table 16.

As for QoS constraints for the different kinds of applications, we set them by referring to the standards recommended in ITU-T Y.1541 [32] as stated in section 3.2.

VI. EVALUATION AND ANALYSIS

In this section, we measure and present the power saving potential and performance of our heuristics TEPG, namely TEPG_U (GGR&TAB_LU) and TEPG_I (GGR&TAB_LI), compared with HDEER, SSPF, and MSPF in terms of Power Saving Ratio (*PSR*), Powered-Off Cable Rate (*POCR*), Mean State Switching Times (*MSST*) and Mean Running Time (*MRT*).

Here, we first define a unit step function $unit\,(x)$ as shown in Eq. (22). *POCR*, *MSST* and *MRT* are defined in Eqs. (23)-(25) respectively.

$$unit\,(x) = \begin{cases} 1, & x > 0 \\ 0, & x \leq 0. \end{cases} \tag{22}$$

$$POCR = \frac{\sum\limits_{(i,j)\in E} \left(N_{(i,j)} - n_{(i,j)}\right)}{\sum\limits_{(i,j)\in E} N_{(i,j)}} \times 100\% \tag{23}$$

TABLE 15. Schemes of deployment and configuration over different topologies.

Topologies	BSs	#CHAs	#/LCs	#Ports
CERNET2	2/4/6/8/10	20/21/25/26/39	26/44/70/88/114	88/176/264/352/440
CANARIE	2/4/6/8/10	31/33/44/46/65	46/78/124/156/202	156/312/468/624/780
GéANT	2/4/6/8/10	49/57/78/83/113	83/146/229/292/375	292/584/876/1168/1460
INTERNET2	2/4/6/8/10	64/67/84/87/136	87/156/243/312/399	312/624/936/1248/1560

TABLE 16. Power consumption parameter values used in simulation.

Parameter	Value
Power consumption of a master engine	356W
Power consumption of a chassis	100W
Maximum power consumption of a forwarding engine	446W
Maximum power consumption of a replication engine	100W
Maximum power consumption of a port	100W
Power consumption of an optical pre-amplifier	4.8W
Power consumption of an optical in-line amplifier	10W
Power consumption of an optical post-amplifier	4.8W
Power consumption of an optical regenerator	26W

$$MSST = \sum_{(i,j)\in E} \sum_{(i,j)_k \in (i,j)} unit\left(CableSt^{\text{cur}}_{(i,j)_k} - CableSt^{\text{pre}}_{(i,j)_k}\right) \tag{24}$$

$$MRT = \frac{t_D^{\text{ALGO}}}{Num\,(D)} \tag{25}$$

In Eq. (24), $CableSt^{\text{cur}}_{(i,j)_k}$ and $CableSt^{\text{pre}}_{(i,j)_k}$ denote the current and previous states of cable $(i, j)_k$ respectively. In Eq. (25), t_D^{ALGO} denotes the time spent on routing all the traffic demands in D via the algorithm ALGO, and $Num\,(D)$ denotes the number of traffic demands in D.

We take the traditional over-provisioning network design deployment as the power benchmark case, where the whole network is active and each link consists of a maximum number of cables, to measure the power saving potential of different policies. Thus *PSR* can be calculated by the following Eq. (26), where $P_{net}^{\text{all\_}active}$ denotes the power consumption of network with an all-active configuration.

$$PSR = \frac{P_{net}^{\text{all\_active}} - P_{net}}{P_{net}^{\text{all\_active}}} \times 100\% \tag{26}$$

Note that 1) when we investigate the impact of different BSs in a link on *PSR*, we fix *MCU* in each cable to 1; 2) when we investigate the impact of *MCU* in each cable on *PSR*, we fix *BS* in each link to 6; and 3) for the rest of parts (the change of *PSR* over time, *POCR*, *MSST* and *MRT*), we fix *BS* in each link to 6 and *MCU* in each cable to 1.

A. PSR PROFILES

We first illustrate the power saving profiles of all investigated heuristics over time for different topologies in Figs. 7(a)-7(d). From these figures, we can observe that 1) the power saving profiles follow a typical day-night trend as expected and more in depth, *PSR*s during the night are higher compared to the day as a consequence of the higher number of links powered off; 2) HDEER has the worst *PSR*s in all the heuristics during the OPPs since the cables run at the lowest rate level in HDEER have still more power consumption than the powered-off cables in the other heuristics, whereas sometimes HDEER is even superior to the other heuristics expect for TEPG_I during the PPs because when almost all cables have been powered on, HDEER can still leverage the speed scaling policy that is missing in the other heuristics to acquire power saving; 3) MSPF usually has larger *PSR*s than SSPF especially during the OPPs, which mainly attributes to the fact the multi-path routing can split the packets belonging to the same flow among multiple paths, improve bandwidth utilization of the cable and thus need fewer powered-on cables than the single-path routing; 4) TEPG_I has the best *PSR*s in all the heuristics whether during the OPPs or the PPs because the smallest network sub-graph can be acquired at the GGR stage, consisting of the ACNN routing stage, the GP stage and the iterative FC stage(s) and GC stage(s) to check the possibility of powering off the remaining network elements according to four combined node-link sorting criteria proposed above, and then the TAB stage in TEPG can further power off as many cables as possible in each bundled link, whereas the routing paths in SSPF and MSPF are generated by *Dijkstra*'s algorithm and *Yen*'s algorithm respectively and their selecting and checking candidate cables only according to the single criterion, namely the smallest average flow per demand and the largest remaining capacity respectively; 5) *PSR*s of TEPG_U are larger than MSPF during the most cases of the OPPs whereas sometimes they are the smallest ones in all the heuristics during the PPs, which mainly benefits from the GGR stage of powering off many idle links during the OPPs vs. awakening them during the PPs; 6) the largest *PSR* up to 80.8% is acquired by TEPG_I during the OPPs over CANARIE when and where the traffic volume is the minimum and thus the network with the fewest number of elements has a largest *PSR*.

To give more insight, we then investigate the impact of different *MCU* on PSR over the different topologies. We carry out the tests only during OPPs in order to guarantee the feasible objective measure and evaluation by supplying the necessary capacity to accommodate the traffic while adopting the low *MCU*. The measured results are illustrated in Figs. 8(a)-8(d). Note that none of all investigated heuristics can route the traffic successfully when the *MCU* are enough low over all the topologies and the left-most horizontal lines

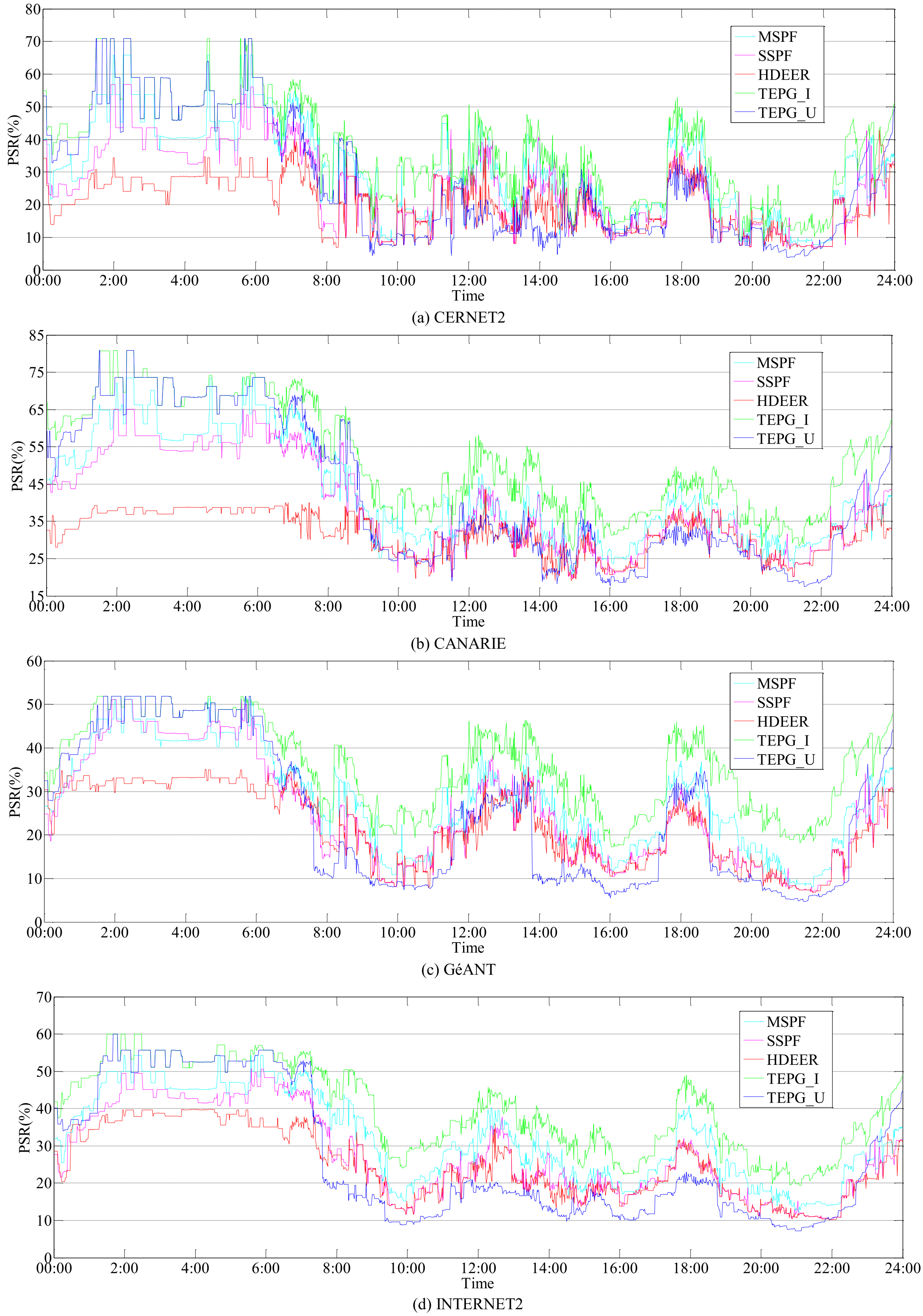


FIGURE 7. ***PSR*** **profiles over time over the different topologies.**

in each figure show the cases. We can observe that *PSR*s of the heuristics except for MSPF are smaller and smaller with the increasing of *MCU*, whereas the PSRs under *MCU* in some cases, such as while $MCU \in (70\%, 80\%)$ over CERNET2 and $MCU \in (65\%, 85\%)$ over GéANT, can be larger than those under smaller *MCU* for MSPF. This result highlights the flexible capability of MSPF in routing traffic demands by its multi-path attribute over the networks where their nodes usually have large degrees. In the worst cases, *PSR*s of HDEER have the sharpest drops down to 12%, SSPF down to 18%, while TEPG_I at most 30%. Moreover, we can observe that *PSR*s of TEPG_U are smaller than those of MSPF under large *MCU* over GéANT and INTERNET2 since more redundant network elements in TEPG_U have to be powered on as the result of a longer average path length from larger network diameters. By contrast, we can observe that TEPG_I has the largest and the most stable *PSR*s for the different *MCU* which mainly attributes to it can track traffic fluctuation by only powering on the necessary number of network elements as few as possible relying on its capability from the power-aware routing in the TEPG stage and high resource utilization via TAB_LI.

In the following, we further extend our investigation to the impact of different *BS*s in a link on *PSR* over the different topologies, illustrated in Figs. 9(a)-9(d). We can observe that under the scenarios of different *BS*s during PPs and OPPs over four topologies, TEPG_I has the largest *PSR*s of all heuristics all the time and MSPF usually has larger *PSR*s than SSPF. Besides, HDEER has the smallest *PSR*s of all heuristics during OPPs over four topologies, and TEPG_U has the smallest *PSR*s during PPs over the other topologies except for SSPF with the smallest *PSR*s during PPs over CANARIE. The reasons are similar to those of *PSR*s over time analyzed above. Moreover, we can also observe that during OPPs over four topologies, TEPG_U has larger *PSR*s than MSPF when $BS=2$ versus smaller than MSPF when $BS \in \{4, 6, 8, 10\}$ and TEPG_U has larger *PSR*s than SSPF when $BS \in \{2, 4\}$ versus smaller than SSPF when $BS \in \{6, 8, 10\}$. The result can be expected because the larger *BS* in each link can give finer granularity and more flexibility for MSPF in powering off cables in links as opposed to any an awaken cable of a sleeping link causing the entire link powered on in TEPG_U. Besides, HDEER has smaller *PSR*s than MSPF but larger than TEPG_U during PPs over CANARIE for all sizes of BSs, whereas even larger than MSPF and only smaller than TEPG_I during PPs over the other topologies for all sizes of *BS*s. This is because when more and more cables are powered on, HDEER can further accomplish the additional power saving by adjusting link rate adaptively.

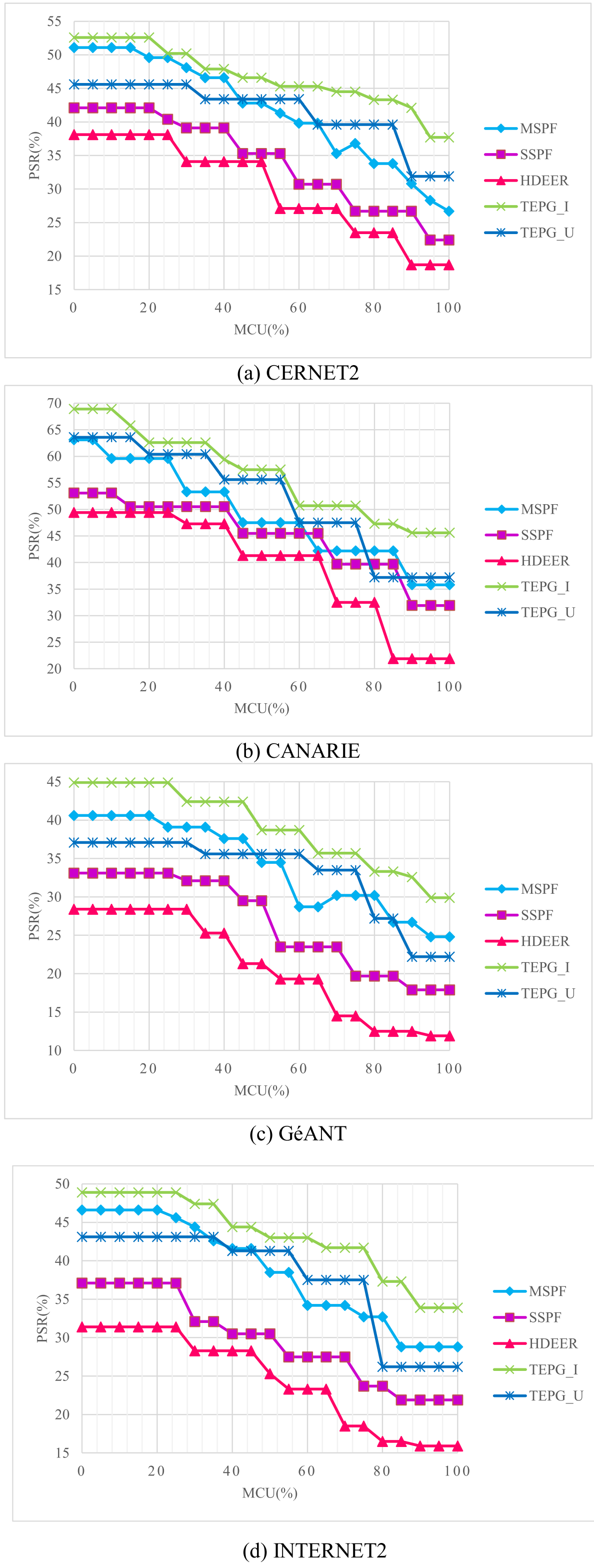


FIGURE 8. ***PSR*** **profiles under** ***MCU*** **during OPPs over the different topologies.**

B. POCR

Due to none of cables powered off in HDEER, we only illustrate *POCR*s of the other four heuristics during PP and OPP over different topologies in Fig. 10. By comparing the histograms we can observe that among the heuristics over four topologies, the solutions yielded by TEPG_I in CANARIE lead to the largest *POCR*s of about 78% during OPPs and about 28% during PPs, and in contrast, the solution yielded by

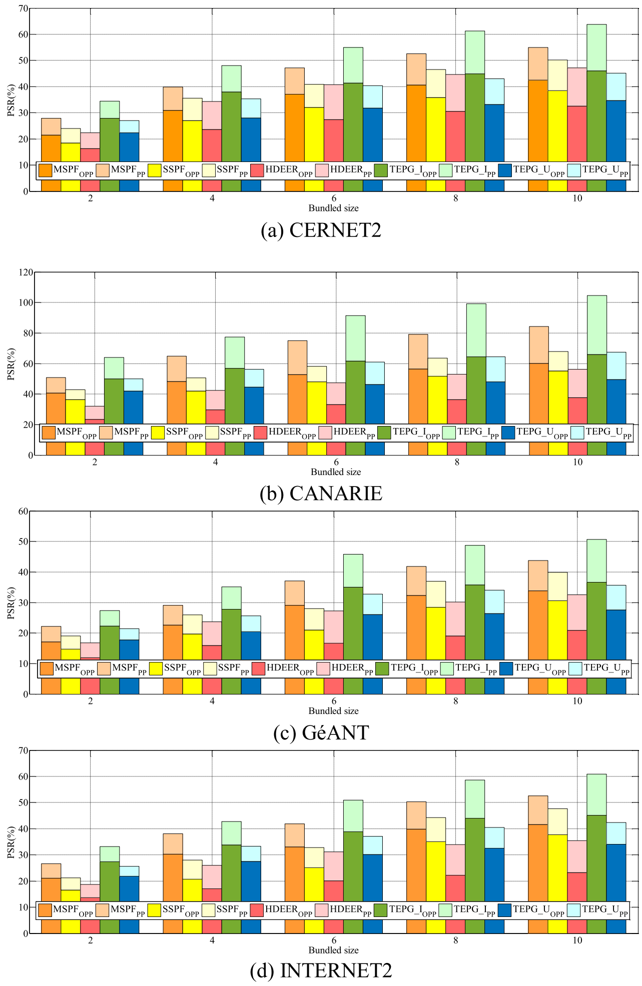


FIGURE 9. ***PSR* under *BS*s during OPPs and PPs over the different topologies.**

MSPF in GéANT leads to the smallest *POCR* of about 23% during OPPs and the solution yielded by TEPG_U in GéANT leads to the smallest *POCR* of about 7% during PPs. Note that the cables powered off in TEPG_U come entirely from the powered-off bundled link owing to the TEPG stage which shows significant powering-saving benefits during OPPs. TEPG_U can thus power off even more cables than SSPF and MSPF during OPPs. Nevertheless, the sharp increase of traffic load during PPs tends to weaken the saving share achieved by the TEPG stage, which gradually deteriorates the *POCR* of TEPG_U and make it even have the lowest *POCR* during PPs among the heuristics over four topologies. Moreover, from the above prominent performances of TEPG_I, we can also realize that the TAB_LI stage plays an extremely important role in reducing the power consumption during PP and confirm that the TAB_LI stage jointly with the TEPG stage is indeed able to accomplish a considerable amount of power saving. Interestingly, although *PSR* of SSPF is smaller than that of MSPF as shown in Figs. 9(a)-9(d), SSPF can still power off more cables than MSPF during OPPs as shown in Fig. 10. This is mainly because the majority of the powered-off cables in MSPF are attached to the different network elements (LCs even CHAs), which can bring the great possibility to power off more network elements than SSPF and thus gain the further more power saving based on the fact that the benefits of powering off LCs or CHAs are far beyond the ones from powering off the cables.

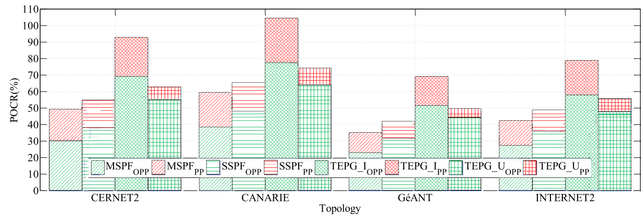


FIGURE 10. **POCR during OPPs and PPs over the different topologies.**

C. MSST

MSST can reflect the stability and running overhead of the solution yielded by heuristics. *MSST*s of all investigated heuristics at a 24h time scale over different topologies are illustrated in Fig. 11. It can be seen that MSPF shows far more *MSST*s than the other heuristics especially in the topologies of GéANT and INTERNET2 since more cables are involved and have to switch their states due to the *Yen*'s algorithm [35] based multi-path routing once the traffic fluctuation occurs. In the contrary, TEPG_U has the fewest *MSST*s due to its excellent traffic fluctuation tolerance from the consistent state of its cables forming a bundled link. HDEER has only more *MSST*s than TEPG_U and thus better stability than the other three heuristics owing to a certain degree of traffic fluctuation tolerance among rates and the significant improvement in determining dual rate switching thresholds by statistical methodology. TEPG_I has more *MSST*s than HDEER, which is mainly because the bad tolerance of TEPG_I for traffic fluctuation attributed to its striving for a minimum powered-on network subset. Furthermore, the cables forming a bundled link are powered off as a whole in the GGR part of TEPG_I, which makes TEPG_I show fewer *MSST*s than SSPF. Unexpectedly, we also note that the *MSST*s in GéANT are fewer than those in INTERNET2, which indicates that both network diameter and the degree of nodes will also impact *MSST* to some extent.

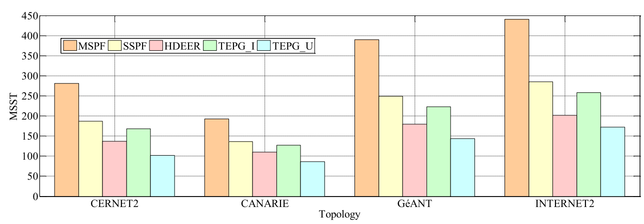


FIGURE 11. **MSST over the different topologies.**

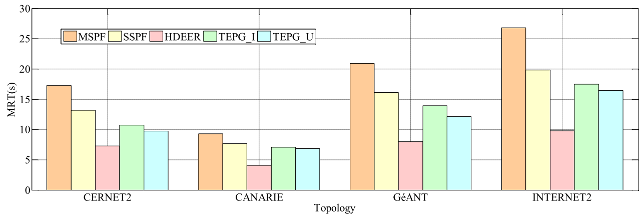


FIGURE 12. Comparisons on *MRT*.

D. MRT

The *MRT*s of all investigated heuristics over different topologies are shown in Fig. 12. Notice that HDEER has far less *MRT* than the other four heuristics for each topology. The reason for obvious differences is that the distributed routing run in each node of HDEER need only iteratively update the configuration value to seek the Pareto optimal points for minimizing the total energy consumption of the entire network and the total traffic delay of the entire network when the input traffic fluctuates, which is obviously a lightweight running overhead compared with the greedy routing and checking process for powering off network elements in the other four heuristics. Both MSPF and SSPF are devised to carry out an additional recovering process for each powered-off network element according to their previous decisions to check whether more network elements can be powered off, which makes their running take more time than the direct exquisite checking for determining each network element to be powered off according to the different criteria in the routing process of TEPG_I and TEPG_U. Furthermore, more network elements in MSPF need to be checked, which makes its *MRT* larger than SSPF. As for TEPG_I and TEPG_U, we can obverse that the gaps of *MRT*s between them are very small all the time, the former only a little larger than the latter, even over GéANT and INTERNET2, which indicates that time overhead of running TAB process is negligible compared with that of running GGR process.

VII. CONCLUSION

In this paper, we devise power-aware solutions from a view point of TE for green routing and network planning to achieve a substantial power saving in the bundled link based backbone networks. We develop two greedy heuristics TEPG_U and TEPG_I which are both composed of the hop-by-hop routing stage-GGR and the traffic assignment stage-TAB to solve the GRB2 problems based on the different behavior of the cables forming a bundled link. We elaborate GGR in order to obtain a minimum network subset with as few powered-on elements as possible: (i) an available capacity of neighbor nodes based hop-by-hop routing stage-ACNN; (ii) a greedy pruning stage-GP; (iii) a feasible checking stage for routing-FC and (iv) a greedy checking stage for pruning-GC. We adopt the statistical methodology to dynamically estimate traffic matrices as the basis of simulation. We carry out extensive simulations on four real network topologies (CERNET2, CANARIE, GéANT and INTERNET2) under various traffic demands during PP and OPP. We evaluate and analyze TEPG_U and TEPG_I in terms of network power consumption and network performance compared with MSPF, SSPF and HDEER, and conclude that TEPG_U and TEPG_I can solve GRB2 excellently from the different aspects, simultaneously guaranteeing necessary QoS requirements.

Inspired by [48], we shall consider to feed the heuristic solutions into MILP models when our future work extends from the online routing decision problems over IP networks to the offline green routing or green network plan over the optical networks where the solution speed of adopting exact approach based on MILP can be tolerated. We shall also investigate the impact of photonic network coding capabilities permitting mixing of different flows as stated in [49] on efficient resource usage and energy-aware routing over backbone networks in our future research. Furthermore, the generalization of heuristic approaches from small-scale networks to large-scale ones has certain issues and it may not be always the case that the generalization is predicted [50], so we shall verify our heuristic approaches over larger-scale networks in our subsequent work.

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