saving performance of the SR network under two TE schemes. In the first scenario, tunneling is implemented in routing the network traffic while, in the second scheme, no tunneling policy is set for the network controller. In other words, in the latter scenario, the traffic is routed from source to destination with no pre-determined tunnel configuration.

II. RELATED PUBLICATIONS

Existing research on the energy-efficient wireline network can be classified into two solution groups: the local and global energy efficiency solutions. On the local energy-saving level, prior research has largely focused on the Adaptive Link Rate (ALR) [2] [3] and Link Sleep techniques [4] [5] for the realization of energy economy. In ALR, the energy efficiency is achievable by scaling down the link speed. This technique however is less favorable for the data transmission over an extended period due to the poor transmission performance [6]. Meanwhile, with Link Sleep, a non-utilized link is put to sleep and the extent of energy saving is positively correlated to the length of sleep interval. In [7], Gupta and Singh proposed a strategy to alter the state of network interfaces from active to dormant, which was subsequently extensively researched and established as the IEEE802.3az standard [4].

Unlike the local-level solution whose focus is on the energy saving on the link layer, the global-level solution is concerned with the total energy economy of all links or components in a network [8][9][10]. The operating principle of the global solution is either to leverage the graphical topology and individual link utilization statistics for identification of the low-load links to enter sleep mode; or to apply the traffic engineering (TE) to the traffic flow.

In [11], two energy-efficient (*green*) metrics were proposed for augmenting the energy saving of IEEE802.3az hardware, i.e. the Extremely AuGmented Energy efficient etheRnet (EAGER) and Congestion aware Augmented eneRgy efficient Ethernet (CARE) metrics. Nevertheless, in [11], the experiments were carried out on the *distributed* network scheme. On the contrary, in this current research, the assessment of the energy saving associated with the EAGER and CARE green metrics implementation is carried out on an SR centralized network.

Similar to the normal centralized network, either SDN or SR is required in the energy-efficient centralized network operation. On the *green* SDN network, Rasih et al. [12] proposed the energy-efficient SDN network in which MPLS Label Switching Paths (PLSP) was employed for pre-established paths based on the aggregate traffic load of every source-destination pair of the network to reduce the number of paths utilized while increasing the network resource utilization. In [13], an energy-saving mechanism was proposed and applied to a network to reduce the total energy cost by powering off certain links unnecessary for the traffic demand. In essence, the implementation of the *green* SDN network entails the designation of sleep links and the network traffic flow management. The notion of switching off or putting to sleep the SDN network elements for the energy economy has long been studied, e.g. [14][15].

A novel centralized network that utilizes the source routing paradigm, the Segment Routing (SR) network has been proposed in the Internet Engineering Task Force (IETF) [16]. One advantage of SR is its compatibility with TE routing in the *green* centralized network. Carpa et al. [17] proposed the STREETE framework on the energy-efficient SR network that involves three steps: the designation of OFF/ON links, identification of alternative routes, and transmission of new routing instructions to the routers. In essence, the framework simply deployed the rerouting and dynamic reconfiguration in the SR implementation. Nevertheless, no tunneling policy was set in their experimental implementation. Unlike Carpa [17], this current research has investigated the *green* SR network under two different TE schemes: tunneling and non-tunneling.

III. ENERGY-EFFICIENT SEGMENT ROUTING

The proposed global energy-efficient (*green*) SDN-based SR centralized network involves two sequential steps: the green metrics and TE implementation.

Step1 : Green Metrics Implementation

In the first step, either the Extremely AuGmented Energy efficient etheRnet (EAGER) or Congestion aware Augmented eneRgy efficient Ethernet (CARE) approach [11] is deployed to designate the dormant links for realization of the global energy economy. In the sleep links designation, the SR controller negotiates with the routers for statistic messages to establish a virtual topology using the Topology Discovery Process. The controller then generates the source-destination pairs prior to the application of either EAGER or CARE to determine the pre-established path associated with each source-destination pair and subsequently realize the global energy saving. To realize the energy economy, the traffic is aggregated for more non-utilized links which are subsequently put to sleep consistent with the IEEE802.3az standard. It differs from [12],[17], where the pre-established paths are identified and the disable/enable (OFF/ON) switching technique deployed rather than the IEEE802.3az standard.

The Extremely AuGmented Energy efficient etheRnet (EAGER) function is a straightforward *green* metric function. Given a link (i, j) with the link utilization of $L_{i,j}$, the EAGER value of the link can be computed by:

$$EAGER_{i,j} = \begin{cases} 100, & \text{if} \quad L_{i,j} \leq 25\% \\ 1, & Otherwise \end{cases} \tag{1}$$

Under the IEEE802.3az standard, energy saving is possible for the load range of 0 - 25% while none is realized beyond the 25% threshold (i.e. the green threshold). In this research, an EAGER metric of 100 is thus assigned to a low-load link so that new incoming traffic is redirected to another link. On the hand, an EAGER metric is equal to 1 for the load utilization beyond the green threshold.

In the Congestion aware Augmented eneRgy efficient Ethernet (CARE) metric function, in addition to the green threshold (25% link utilization), the CARE *green* metric function incorporates a congestion threshold (>80% link utilization). Specifically, links with utilization beyond the congestion threshold

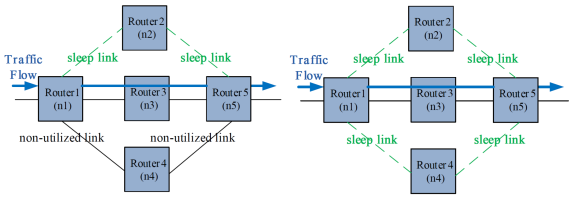
(>80%) are assigned a value of 100. Furthermore, for links with utilization under the green threshold (≤25%), the CARE metric will assign the simple multiplicative inverse of the link utilization. Given a link (i, j) with the link utilization of $L_{i,j}$, the CARE value of this link can be computed by:

$$CARE - X_{i,j} = \begin{cases} \frac{100}{L_{i,j}}, & \text{if} \quad L_{i,j} \leq 25\% \\ 1, & \text{if} \quad 25 < L_{i,j} \leq X\% \\ 100, & \text{if} \quad L_{i,j} > X\% \end{cases} \tag{2}$$

Interestingly, an appropriate congestion threshold for the CARE metric function varies, depending on a number of reasons, e.g. the diverse manufacturer specifications and customer requirements. This experimental research has used the congestion threshold (X) of 80%.

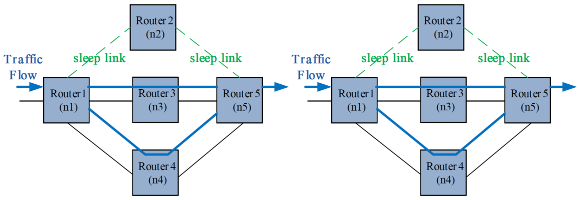
Step2 : TE Implementation

Once shortest path has been computed and the associated SID from controller to the ingress switch, segment routing and so load balancing is applied. As we can see in Fig. 1 more links will be used in this case compare to routing without load sharing. For the sake of comparison, we carried out experiments with the green SDN-based SR centralized network under two TE scenarios of with and without tunneling scheme, as illustrated in Fig. 2.



(a) tunneling (t_1): Controller generates the tunnel (n1-n3-n5) for management of traffic flow. Tunneling contributes to the aggregate traffic.

(b) tunneling (t_2): Controller generates the tunnel (n1-n3-n5) for management of traffic flow. Non-utilized links which are subsequently put to sleep.

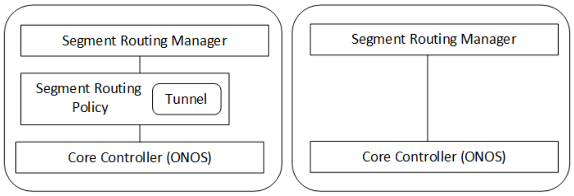


(c) non-tunneling (t_1): Controller has ECMP implementation. All links are utilized links except two sleep links.

(d) non-tunneling (t_2): Controller has ECMP implementation. All links still are utilized links except two sleep links.

Fig. 1: The operations of the SDN-based SR centralized network at t_1 (time 1) and t_2 under the tunneling (a, b) and non-tunneling (c, d) TE schemes

In the first scheme, the pre-established paths of the source-destination pairs are "*tunneled*" for the management of traffic flow. Once the tunnels are configured, the controller then orchestrates the traffic flow in accordance with the tunnel configuration. The tunneling contributes to the aggregate traffic and at the same time idle links which are subsequently put to sleep as per the IEEE802.3az standard.



(a) tunneling

(b) non-tunneling

Fig. 2: The experimental traffic engineering (TE) schemes: (a) tunneling, (b) non-tunneling

The *green* SDN-based SR network with tunneling scheme is algorithmically illustrated in Algorithm 1. In the first phase of the algorithmic scheme (i.e. the green metrics and pre-established paths phase), all the links in the network are assumed to be active and the controller is aware of all the traffic flow in the network. In this phase, the controller calculates the pre-established paths using either the green EAGER or CARE metrics. In addition, the links outside of the pre-established paths (i.e. non-utilized links) are put to sleep in accordance with the IEEE802.3az standard due to no traffic flow. In the second phase (TE with tunneling), the controller generates the tunnels corresponding to the pre-established paths and instructs the segment routers in the network to direct the traffic according to the tunnel configuration.

Algorithm 1: Tunneling TE

```
$X = (1, 1, ..., 1)$ → Initially all the link are active
$F = (f_1, f_2, ..., f_N)$ → Total flows in Network $= N$
/*Phase1-Green Metrics and pre-established paths*/
for each flow $f_i \in F (i = 1, 2, ..., N)$ do
    $S(i)$ ←Pre-established Path (calculate with EAGER or CARE metrics)
    $P_{xy}(i)$ ← Select Path $(x, y)$ (denote Path between source $(x)$ and destination $(y)$)
    $P \leftarrow P_{xy}(i)$
end
/*Phase2-Traffic Engineer with Tunneling*/
for each flow $f_i \in F (i = 1, 2, ..., N)$ do
    Tunnels are set follow Pre-established Path $P_{xy}(i)$
    Controller tells every Segment Routers
    Segment Router update and use tunnel table for transfer traffic $f_i$
end
```

In the second scheme, no tunneling policy is set for the traffic management of the *green* network. Under this condition, the controller designates the links to enter sleep mode from the non-pre-established paths and then computes the shortest equal

Algorithm 2: Non-tunneling TE

```
$X = (1, 1, ..., 1) \rightarrow$ Initially all the link are active
$F = (f_1, f_2, ..., f_N) \rightarrow$ Total flows in Network $= N$
/*Phase1-Green Metrics and Selecting links to sleep*/
for each flow $f_i \in F(i = 1, 2, ..., N)$ do
    $S(i) \leftarrow$Pre-established Path (calculate with EAGER or CARE metrics)
    $P_{xy}(i) \leftarrow$ Select Path $(x, y)$ (denote Path between source $(x)$ and destination $(y)$)
    $P \leftarrow P_{xy}(i)$
    for each link $l_k \in L(k = 1, 2, ..., N)$ do
        $X_k \leftarrow \delta(P_{xy}(i), l_k)$
        \\Sleep links are selected by Kronecker delta function ($\delta$).
        \\Kronecker delta function returns 1 if the link $k$ belong to $P_{xy}(i)$ and 0 otherwise.
        \\keep active link = 1 and sleep link = 0 at $X_k \in X(k = 1, 2, ..., L)$
    end
    Update($X$)
end
/*Phase2-Traffic Engineer with Non-Tunneling*/
Green Virtual Topology is set with sleep links
Controller use green virtual topology and controller tells every SR routers
Every router change the forwarding table to routing over the new paths
```

cost multiple paths (ECMP) of the source-destination pairs, without taking into account the designated sleep links. The sleep links become non-utilized links as per the IEEE802.3az standard and thereby consume little energy.

The *green* SDN-based SR network without tunneling is algorithmically depicted in Algorithm 2. In the first phase of the scheme (i.e. the green metrics and sleep link selection), all the links are active and the controller is aware of all the traffic flow in the network. The controller calculates the pre-established paths of source-destination pairs using the green EAGER and CARE metrics. The Kronecker delta function is used to determine the links outside of the pre-established paths (i.e. non-utilized links). The sleep links are subsequently selected from the non-utilized links prior to the application of the IEEE802.3az standard. In the second phase (TE without tunneling), unlike the SR network with the tunneling TE implementation, no tunneling is generated and thus the sleep links are directly applied to the virtual topology. The controller then computes the shortest ECMP of the source-destination pairs, without taking into account the sleep links.

IV. EXPERIMENTAL EVALUATION

This section deals with the experimental setup of the *green* SDN-based SR network with and without tunneling schemes and the evaluation of both algorithmic schemes on an Abilene network topology and its traffic matrices. Fig. 3 illustrates the 11-core node SR Abilene topology utilized in the global energy saving evaluation of both algorithmic schemes. The nodes (routers) are connected by 10Gbps links. In [18], the traffic matrices were the five-minute average traffic for a period of several months. In this experiment, the traffic matrices (TM) are the averages of the final five minutes of the hour [18] for a period of 24 hours.

In the experimental network, the 11 source-nodes generate the traffic and transmit to the 10 destination-nodes, resulting in a total TM size of 110 (11x10). Each individual router node of the 11-node SR Abilene topology network is connected to an ONOS controller [19]. To achieve the global energy saving, the green metrics (EAGER and CARE) are first integrated into the ONOS controller prior to the application of the tunneling and non-tunneling TE schemes.

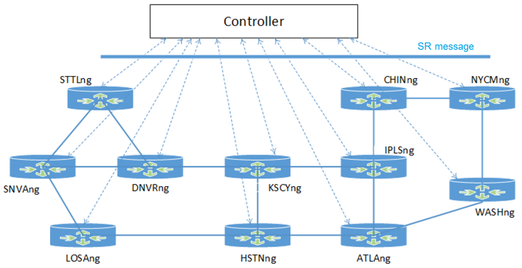
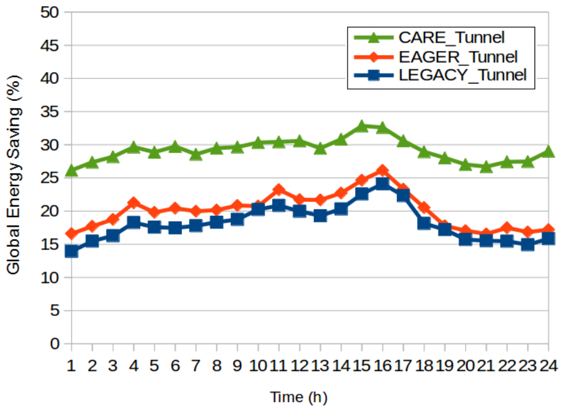


Fig. 3: A depiction of the experimental SDN-based SR Abilene topology network

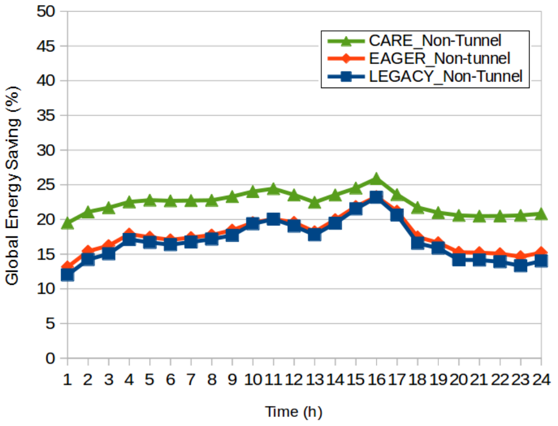
To obtain the energy consumption for subsequent calculation of energy saving associated with the network links, the 10GBASE-T power consumption against load curve [20] was utilized by applying the Poisson traffic to the IEEE802.3az standard. In [20], simulations were carried out on a 10Gbps link and it was reported that the energy consumption increased with the traffic load and reached the full energy consumption (100%) with a mere 24% link utilization. As previously mentioned, since all router nodes are linked to the controller, the controller negotiates the router statistics for their respective link load. The link load is algorithmically compared against the consumption-load curve for the energy consumption of each link. The energy consumption is converted into the link-level energy *saving* and subsequently the network-level (global) energy saving.

Figs. 4(a)-(b) illustrate the global energy saving of the Abilene SR topology network using three different metrics under the tunneling and non-tunneling TE schemes, respectively. The three metrics are the LEGACY, EAGER and CARE metrics. In LEGACY, the pre-established paths are determined by the conventional metric and the IEEE802.3az standard applied to the low-traffic links. EAGER and CARE have been previously discussed.

Under the tunneling scheme (Algorithm 1), CARE could achieve a higher overall energy saving than EAGER and LEGACY. The largest energy saving gain (i.e. the differences between energy saving) of two times (2X) was achieved with



(a) tunneling



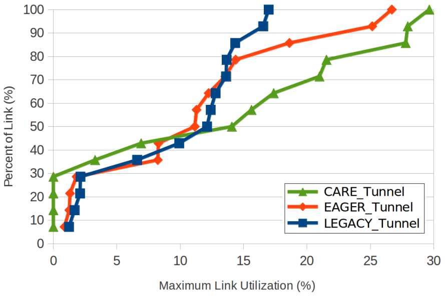
(b) non-tunneling

Fig. 4: The global energy saving of the SDN-based SR Abilene topology: (a) tunneling, (b) non-tunneling

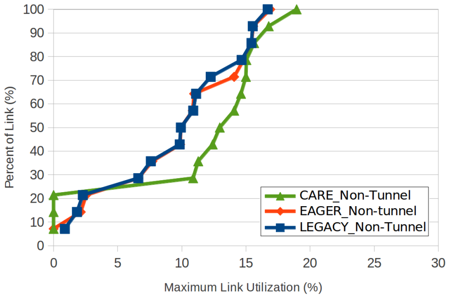
the CARE metric (relative to LEGACY) at termination (at the 24^{th} hour). The low global energy saving under LEGACY was attributable to the absence of green metrics other than the IEEE802.3az standard. The nonexistence of green metrics in LEGACY contributed to non-aggregate traffic and few sleep links. In this research, the traffic matrices (TM) were observed hourly for a period of 24 hours since the energy saving levels are correlated to the traffic matrices (TM) on the network.

By comparison, under the non-tunneling scheme (Algorithm 2), the algorithm would resort to the shortest equal cost multiple paths (ECMP) and the subsequent traffic dissipation. Under this TE scheme, the largest energy saving gain achieved under the CARE metric was 1.6X at the end of the 1^{st} hour.

Fig. 5 compares the cumulative distribution functions (CDF) of maximum link utilization (MLU) of the first hour between the three metrics under the two TE schemes. Under the tunneling TE scheme (Algorithm 1), the MLU increased nearly 30% with the CARE metric vis-à-vis the 17% with LEGACY. The greater MLU was attributable to the more aggregate traffic and greater numbers of non-utilized links. The increase (13%) was nonetheless small, suggesting the minimal impact of the CARE-tunneling scheme (Algorithm 1) on the MLU. Meanwhile, under the non-tunneling TE (Algorithm 2), the

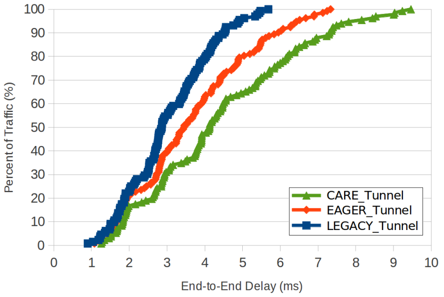


(a) tunneling

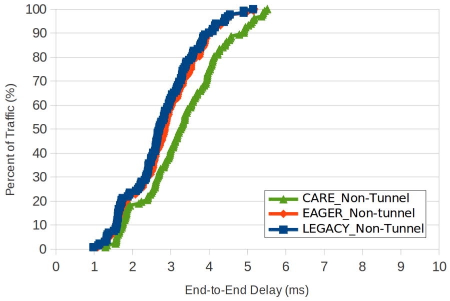


(b) non-tunneling

Fig. 5: CDF of maximum link utilization on the SDN-based SR Abilene network: (a) tunneling, (b) non-tunneling



(a) tunneling



(b) non-tunneling

Fig. 6: The CDF of end-to-end delay on the SDN-based SR Abilene network: (a) tunneling, (b) non-tunneling

increase in MLU under CARE was significantly less (19%) and that belonging to LEGACY was similar to that under the tunneling scheme (17%).

Fig. 6 compares the CDF of end-to-end delay between the three metrics under the two TE schemes. Under the tunneling scheme with the CARE and EAGER metrics, the end-to-end delay became lengthier. On the other hand, under the non-tunneling TE, the end-to-end delays with the three metrics (LEGACY, EAGER and CARE) were essentially similar. In short, the experimental findings revealed that the higher global energy saving on the Abilene segment routing (SR) network could be achieved with the CARE-tunneling TE scheme.

V. CONCLUSION

The paper studies green traffic engineering in centralized SDN environment through segment routing. This experimental research has evaluated the global energy saving performance on SDN-based SR centralized network under two IEEE802.3az-incorporated algorithmic schemes, i.e. the green (EAGER and CARE metrics) SDN-based SR networks with and without TE tunneling. Results put forward on real internet topology the advantage of the green metrics and the inconvenience of load sharing policy, i.e. the non-tunneling policy, for energy saving purpose. The experimental results showed that the overall (global) energy saving realized under the CARE-tunneling strategy was twice that of the conventional metric with TE tunneling (LEGACY tunneling strategy). Meanwhile, the global energy efficiency under the EAGER-tunneling scheme was comparable to the LEGACY tunneling strategy. On the other hand, the energy saving performance achieved under TE non-tunneling (all three metrics) was inferior to those with tunneling. Nevertheless, the non-tunneling course exhibited the lower end-to-end delay and lower maximum link utilization (MLU).

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