Disruption-Free Link Wake-Up Optimisation for Energy Aware Networks

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Abstract. Energy efficiency has become a major research topic in the Internet community as a result of unprecedented rise in the Information and Communication Technology (ICT) sector. One typical approach towards energy efficiency is to select a subset of IP routers or interfaces that will go to sleep mode during the off-peak period. However, on-the-fly network reconfiguration is generally deemed harmful especially to real time packets due to routing re-convergence. In this paper, we develop an efficient algorithm for achieving energy efficiency which is disruption free. The objective is to incrementally wake up sleeping links upon the detection of increased traffic demand. Unlike normal approaches of manipulating link weights or reverting to full topology in case of even minor network congestion and thereby sacrificing energy savings, our algorithm wakes up the minimum number of sleeping links to the network in order to handle this dynamicity. The performance of our algorithm was evaluated using the GEANT network topology and its traffic traces over a period of one week. According to our simulation results, up to almost 47% energy gains can be achieved without any obstruction to the network performance. Secondly, we show that the activation of a small number of sleeping links is still sufficient to cope with the observed traffic surge.

1 Introduction

The recent rapid growth of Internet has led to the unprecedented rise in energy consumption. According to a number of studies, ICT alone contributes up to 2 – 10% of world's power consumption and this is expected to rise in the near future [1 – 5]. The issue is that there is high level of bandwidth resource underutilisation in the current Internet due to over-provisioning of resources by telecom operators. However, this figure does not depict the actual power usage since the power consumption of networking devices does not scale with current load. On the other hand, with the advent of real time streaming multimedia applications which often require reliable network connectivity, the re-convergence period of the IP routing tables upon topology changes poses a major concern if sleeping and restoration technologies are applied. Typically, current interior gateway protocols (IGPs) like Open Shortest Path First (OSPF) or Intermediate System - Intermediate System (IS-IS) take about hundreds of milliseconds to re-converge, which is not desired when supporting seamless transmission of real-time multimedia content. The use of IP Fast ReRoute (IPFRR) has been proposed by Internet Engineering Task force (IETF) to reduce the reaction time to tens of milliseconds [6, 7].

A common practice for achieving energy efficiency following a time driven approach is to pre-configure a network topology with reduced capacity for energy savings during a given period of off-peak time. This is because network devices consume maximum amount of energy on both idle and underutilised conditions [29]. However, the assumption is that within this energy saving period, the network will be able to handle any traffic surge without causing traffic congestion. This implies that the only solution to tackle unexpected traffic surge beyond the reduced network capacity is to revert to the full network topology and thereby sacrificing energy savings. In most cases, one may observe that the *incremental* wake-up of a small number of sleeping links back to the working state could have handled such traffic uncertainty. In addition, in order to avoid traffic disruptions caused by routing re-convergence upon link wake-up operations, it is also desirable to prioritise the wake-up of those links which will not incur any routing re-convergence and, as a consequence, traffic disruption.

In this work, we propose an efficient algorithm for incremental and opportunistic link wake up operation when it is necessary. We exploit the fact that since many links are underutilised when traffic demand is low during off-peak time, putting such links to sleep mode without incurring traffic congestion to the remaining active links leads to significant energy savings. Based on the reduced topology, we propose an algorithm called Disruption-free Link Wake-up Optimisation Technique (DLiWOT) for enabling incremental link wake-up operations. Upon the detection of network congestion at some active links, this algorithm aims to identify the minimum set of sleeping links to wake up in order to handle potential congestion, while still leaving the remaining sleeping links in standby mode for energy efficiency. The novelty here is a disruption-free proactive mechanism to incrementally avoid congestion risks without necessarily resorting to full topology activation.

According to OSPF/ISIS operation, upon a topology change (e.g. when a link is added to the active network topology), all affected routers need to update their respective routing tables upon re-calculating shortest paths to their destinations. This transient period of several hundred milliseconds poses potential disruption to real time traffic flows. By taking into account this issue, we design the DLiWOT scheme for waking up sleeping links but without incurring any re-convergence procedure. Specifically, the wake up of such links remains only known by their head nodes which will then intelligently divert traffic onto them *locally*, but without further announcing these newly added links to any other remote routers. This is the main improvement with respect to our previous work in [8]. In order to realise DLiWOT, we employed the same network monitoring and control technique as in [9]. In this approach, with the help of traffic engineering (TE) link state advertisements (LSAs) [10], a network control server (NCS) keeps a logical view of the network topology and traffic conditions. The NCS periodically monitors the network conditions at a given time interval which can be determined by the network administrator. Upon the detection of any active link suffering from congestion, the NCS then applies DLiWOT to identify the necessary sleeping links to wake up for traffic diversion. It is also the responsibility of the NCS to actually trigger the wake-up of the identified sleeping links for appropriate traffic diversion.

As we will show through simulations using the GEANT network topology and its real historical traffic traces, DLiWOT is capable of achieving significant energy gains of up to almost 47%, compared to using the full network topology for congestion alleviation, and in a completely disruption-free manner at all times.

2 Related Work

This section summarises relevant works for achieving green ISP networks. Since the amount of energy saving depends on the number of removed links, most existing energy schemes rely on link removal as the main energy saving strategy. Research has also shown that line cards contribute up to 43% of routers energy consumption [11, 12], so link (and the associated line card) sleeping, when implemented properly, can lead to significant overall energy savings. The authors of [13] first suggested a number of approaches for energy savings in the current Internet. These include both network-wide and link-level approaches. According to the network-wide approach, during low link utilisation, the traffic is aggregated into few routes in order to turn off some router interfaces to sleep mode. Link-level approaches involve only local decisions without affecting the operation of the entire network. Numerous proposals have been made in the literature which are summarised in [14, 15].

It has been observed that many operational networks have diurnal traffic patterns that can be regular [16] and this is exploited in energy savings as in [17]. The authors propose a time-driven link sleeping algorithm for energy savings that deploys a multi topology routing protocol to switch between full and reduced topology. In [18], the number of network configurations was considered. The authors showed that their algorithm is able to identify the minimum number of network configurations and time duration within a day for them to be enforced. This maximises energy savings and minimises protocol overhead. However, this is on the condition that regular traffic matrices (TMs) are applied which is not always the case and therefore does not guarantee network robustness to dynamic traffic conditions.

Concerning the issue of routing re-convergence, the authors of [19] propose a hybrid IP-MPLS solution during transient periods for re-convergence avoidance. The authors of [20] propose an offline algorithm for selecting links whose set of traffics can be rerouted in the network without causing any traffic disruption and using the existing Fast Reroute technique, the traffic can be diverted. The authors of [21] investigate the manipulation of network link weights in order to redirect traffic to a particular path while the free links are set to sleep mode for energy savings. Also, [22] employs the use of link weight manipulation in such a way that each step is loop free. A resource management approach was employed in [28] while [29] considered hardware support for online traffic scaling. In [8], the wake up scheme does not consider the routing convergence of the whole network; [23] deployed a combined layer approach by using dynamic circuit to establish bypass links. However, our work is purely a non-disruptive IP layer approach with no additional cost at the routing protocol level.

3 Problem Statement

Let us consider a directed and connected network graph G consisting of a set of vertices $V,$ connected by a set of edges $E,$ and denoted as $G\ (V, E)$. V represents the network nodes/routers while E represents the set of network links. $N = |V|$ is the total number of nodes and $L = |E|$ is the total number of links in the network. Each link is associated with a link weight for computing shortest paths in IP routing and all links are assumed to be symmetrical. Table 1 below summarises specific parameters associated with the problem.

Table 1. List of Symbols.

Variable	**Description**
P_{ef}	Energy efficiency
ℓ_{ij}	Link connecting nodes i & j in that direction
t^{sd}	Total traffic demand from source (s) to destination (d)
ℓ_{ij}^{sd}	Traffic flow from s - d that is routed through ℓ_{ij}
L_{ij}	Total traffic load on link ℓ_{ij}
T	Threshold value for network link utilisation conditions
c_{ij}	Link Bandwidth
S_c^{sd}	Set of links in congested path routing traffic from s to d
S_n^{sd}	Set of links in new path routing traffic from s to d
ℓ_c	Congested link
E_s	Set of sleeping links

We therefore formulate an Integer Liner Programming (ILP) formulation of our problem where the objective function is to maximise P_{ef} subject to the constraints as explained below:

$$max\ P_{ef} \tag{1}$$

Subject to:

$$\sum_{j=1}^{N} \ell_{ij}^{sd} - \sum_{j=1}^{N} \ell_{ji}^{sd} = \begin{cases} t^{sd}, & \forall s, d, i = s \\ -t^{sd}, & \forall s, d, i = d \\ 0, & \forall s, d, i \neq s, d \end{cases} \tag{2}$$

$$\frac{1}{c_{ij}} L_{ij} \leq T \quad \forall \{i, j\} \in E \tag{3}$$

$$S_n^{sd} \cap \ell_c = \emptyset \qquad \forall s, d \mid \ell_c \notin E_s \tag{4}$$

The objective function of our research work is to increase network energy saving gains as much as possible, which is stated in equation (1). Equation (2) is the flow conservation constraint such that $\ell_{ij}^{sd} \geq 0$ over any network link where s and d are such that $\{s, d\} \in V.$ Equation (3) preserves the individual link utilisation and by extension, the maximum link utilisation (MLU) in the network. This implies that it controls the congestion level of the network. Once the value of MLU is more than the set threshold, the network is considered to be congested. Note also that this equation is the primary determinant for the number of links that can go to sleep or need to be woken up in the network. The higher the threshold value, the more the chances of links to be put to sleep and fewer links to be woken up to handle traffic upsurge. Also, the considered TM contributes to the number of initially pruned links in the network; as such, deploying the TM with the least utilisation level for the period of consideration gives maximum link removal. The selection of the minimum number of links to wake up in order to alleviate congestion as a result of traffic surge is stated in equation (4) and should be such that if –

$$S_c^{sd} = \{s, R_1, R_2, R_3, \dots, d\} \tag{5}$$

where R_1, R_2, R_3 are the set of nodes of the congested path and the congested link is, for example, $\ell_c = \ell(R_1 \to R_2)$, then, S_n^{sd} must not contain $\ell(R_1 \to R_2)$ such that equation (4) is obeyed. This constraint makes it possible that at each iteration of the algorithm, only the shortest path that excludes the congested link will be considered during wake up operation.

The value of P_{ef} can be evaluated by considering the energy consumed by the full and pruned topology respectively. More so, since some links are woken up to the network within some time interval during operational runtime, the link power contributions are also considered as shown in equation (6). P_f and P_p represent the energy consumption of the full and pruned topologies respectively while P_w is the energy consumption of the wake up links.

$$P_{ef} = \frac{\sum P_f - \sum P_p + \sum P_w}{\sum P_f} \tag{6}$$

The presented ILP falls under the class of capacitated multi-commodity minimum cost flow problem and is known to be NP-hard [24]. Therefore, only trivial cases like small networks can be solved using exact method. As such, we explore a heuristic approach to solving it.

4 Scheme Description

Before presenting the generic algorithm, we first illustrate the core underlying principle using the synthetic network topology in Fig. 1.

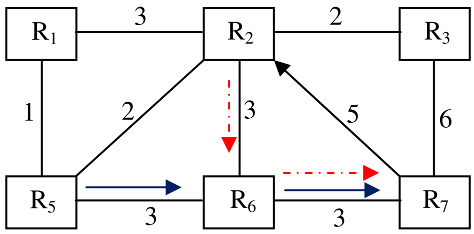

Fig. 1. A synthetic network topology.

The network contains 6 nodes and 18 symmetrical links of equal bandwidth capacity of 10 Mbps. Let's assume that $\ell(R_2 \to R_7)$ is the only sleeping link with the assigned link weight of 5 (as such, the directed arrow in Fig. 1 means that between R_2 and R_7, only $\ell(R_7 \to R_2)$ is active). Assume that at time t_1, the following source destination pairs route 5 Mbps of traffic in the network: {R_5, R_7} through $R_5 \to R_6 \to R_7$, and {R_2, R_7} through $R_2 \to R_6 \to R_7$. This implies that the link load on $\ell(R_6 \to R_7)$ at that time becomes 10 Mbps, implying a link utilisation of 100%. Assume a link utilisation threshold of 90% indicates that a link is vulnerable to congestion. In this case, if $\ell(R_2 \to R_7)$ is added to the network in order to relieve congestion by diverting traffic away from link $l(R_6 \to R_7)$, routing of R_5 does not change since R_5 does not make use of $\ell(R_2 \to R_7)$ to route traffic (whether active or non active). Only traffic from R_2 is diverted through $\ell(R_2 \to R_7)$. We refer to such links as stub links – a stub link is a link that is used by only its own head node for traffic forwarding, but no traffic originated further beyond the local head is routed through this link. It can be inferred that existence of stub links depend on the physical network topology as well as its IGP link weight setting. As such, when restored to the topology for congestion avoidance, even if their restoration is advertised to remote routers, it does not lead to any remote router updating its routing table. If we now consider that the link $\ell(R_2 \to R_7)$ has a link weight of 3 instead of 5 as used before, the routing of the network will change during the wake up process. In that case, if the link is restored to alleviate congestion and its restoration is advertised to the remote routers, router R_5, in addition to router R_2, will also use the advertised link to route traffic to R_7. This can be referred to as congestion diversion instead of congestion avoidance since the utilisation of the added link $\ell(R_2 \to R_7)$ will become the same as that of the previous congested link in the network i.e. $\ell(R_6 \to R_7)$. In that case, link $\ell(R_2 \to R_7)$ can be said to be a transit link - transit links are those links that can be used by other remote nodes to route traffics and therefore are prone to causing disruption when added to the network [8]. It is also worth noting that the classification of these links is based on the pruned topology.

Detailed Operation of DLiWOT - due to the dynamicity of today's traffic, the wake-up algorithm is provided as a proactive measure to control network traffic. DLiWOT is an online congestion control algorithm that is executed at the NCS which exploits the traffic engineering opportunity provided by IP interior routing protocols like OSPF and traffic measurements. This is unlike most energy saving schemes that combine the functionalities of both IP and other existing networks. De facto, OSPF-TE provides special technique for optimising operational performance of a network through the use of opaque LSAs in disseminating TE information. Such TE-LSAs contain basic information for the NCS's decision which includes: maximum link bandwidth, TE metric, router address type/length/value etc. This is in contrast with the normal paradigm in traditional OSPF which is based on static path routing without recourse to network utilisations or energy efficiency, except link bandwidth.

The NCS periodically polls this information from each node, and hence, is able to keep a record of the details of the traffic conditions within the network. The link utilisation is calculated at a certain period of time according to the network administrator's preference. Once it exceeds a set threshold value, DLiWOT is applied by the NCS to identify the alternative paths for possible diversion of traffic from the congested links (see Fig. 2 for the DLiWOT algorithm). This is done by identifying the source nodes of the traffic flows through the congested links and sorting them in a descending order according to their respective bandwidth demands. The descending order approach helps in preventing waking up of excessive sleeping links since only the minimum number of flows (causing the link to be above the utilisation threshold) will need to be diverted instead of many low demand flows possibly scattered along different routes. The selection of the minimum number of links to wake up in order to support any traffic surge should be such that equation (4) is adhered to. Therefore, the set of links on the new path should be devoid of the congested link if traffic is to be diverted away from it, while still maintaining the source-destination pairs of the packet. Secondly, the network threshold value must conform to equation (3). That is, no link's utilisation should be higher than the set threshold value at any point in time; otherwise, the link is said to be congested. The variables x, y, and m are used in the algorithm as counters. In order to adhere to the re-convergence avoidance criteria, selection of stub links is prioritised. This is because the addition of stub link does not cause the diversion of any traffic originated from remote nodes, except the local traffic originated by the head node of the added link. As such, for stub link wake up, there does not need to be any special action taken to prevent link advertisements from reaching remote routers. Each packet flow in the network consists of packet source and destination in its packet header. Therefore, DLiWOT initially checks if each flow's source node has any sleeping stub link that can possibly divert such traffic away from the congested link as shown in the algorithm. If such link exists, the link is added into the logical topology and the MLU of the network is recalculated to ensure that the added link does not cause congestion to the alternate path. If the network is free from congestion, the algorithm returns the current topology to the active state; otherwise, the next stub link is explored. This process is continued for transit sleeping links only if the addition of stub links does not resolve the network congestion. In transit link consideration, in order not to cause traffic disruption, transit link restoration is not advertised, so remote routers remain oblivious to the changes in the topology due to the restored link(s). The NCS locally activates the transit links in order to alleviate the congestion at that period of time.

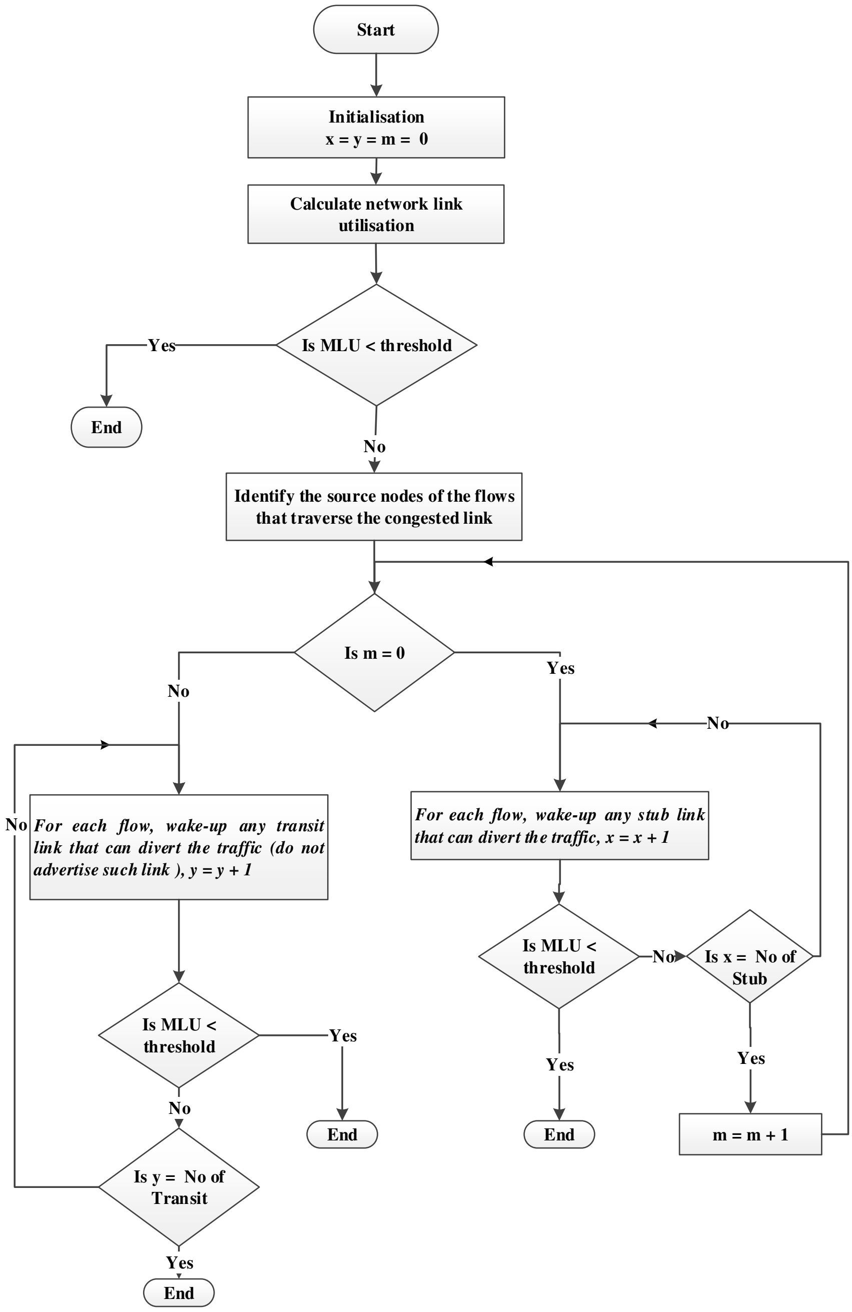

Fig. 2. Proposed DLiWOT algorithm for link wake-up.

5 Performance Evaluation

It can be easily inferred that the proposed link wake up technique can be applied on top of any existing link sleeping optimisation scheme which provides the input of the pruned topology. There can be two common options of deploying the pruned topology, and using DLiWOT to restore sleeping links to it: (1) applying the pruned topology at the lowest utilisation point within every 24 hour period and use DLiWOT till the end of the pre-defined off-peak period; and (2) applying the pruned topology at the beginning of the off-peak period and use DLiWOT till its end. In this paper, we chose the second option. In our case, off peak period is defined from 8 PM to 8 AM, meaning that the pruned topology is applied at 8 PM every day and DLiWOT is applied from 8PM until 8 AM. During the peak period, the full topology is used. The determination of the off-peak time is up to the operator, and in this paper the chosen period is only representative.

In order to assess the performance of our algorithm, we consider the GEANT operational network in which the TMs vary according to a "peak- off-peak" pattern. The GEANT topology is an operational network in Europe for research purposes with 23 point-of-presence nodes, and 74 links. The TMs used for the simulation contain 672 traffic matrix instances generated in one week at every 15 minutes interval [25]. Furthermore, we took into account that the actual energy consumption of a link is not proportional to the link utilisation rate but on the power consumption of the line cards [26]. Therefore, we deployed the energy consumption model of the line cards as stated in Table 2 in calculating their respective energy rates and the savings.

Table 2. Power consumption rate of router’s line cards [11, 27].

Line card	Speed (bps)	Power (Watts)
1-Port OC-192	9953280	174
2-Port OC-48	4976640	160
1-Port OC-48	2488320	140
1-Port OC-3	155520	60

Fig. 3 compares the average utilisation level of the original full topology with topology derived using the DLiWOT scheme using the pruned topology as a starting point. As it can be seen, during the period under consideration, there is an increase in the average link utilisation (ALU) for DLiWOT in all the seven days. This means that the application of DLiWOT can minimise underutilisation while providing energy savings at the same time. The lower spikes correspond to weekend traffic, when traffic is at its lowest value. For example, in the first day during the off peak period when the algorithm was deployed, the highest ALU of the full topology is barely 6% while it is more than double when DLiWOT was applied.

Another novelty of our algorithm is that the congestion control is network based and not link based. This implies that if there is congestion at more than one link, the algorithm returns the minimum number of links to relieve all congestions and in a non disruptive way. Fig. 4 shows the performance of the algorithm when applied to GEANT for a period of 7 days based on the MLU. The graph shows that despite the application of a pruned topology over the considered period, the MLU is not more than 100%. This is based on the deployment of DLiWOT. For example, during our simulations, the number of added sleeping links during the week is shown in Fig. 5. The TM id depicts the actual traffic matrix that caused the congestion while the vertical axis depicts the number of woken up links to control such congestion. In the graph, it is obvious that just the addition of 4 links in each case controlled such congestion while other schemes would have reverted to the full topology and thereby waking more than 30 links up. The number of added links also affected the energy savings in the period as shown in Table 3. Therefore, one can infer that the addition of few links can actually keep the congestion level below a set threshold instead of reverting to the full topology and thereby sacrificing energy savings. Due to the robustness of our scheme in congestion control, its application period can be extended for use beyond the off-peak period. The only difference being that more links may have to wake up during the peak period, if congestion occurs.

As mentioned, in order to control traffic disruption during wake up of links and minimise the number of link restoration advertisements that need to be prevented from reaching remote routers, DLiWOT prioritises the waking up of stub links before transit links. For transit links addition, the links are not advertised to the network. Therefore, the added links do not result to any count to infinity or bouncing effect.

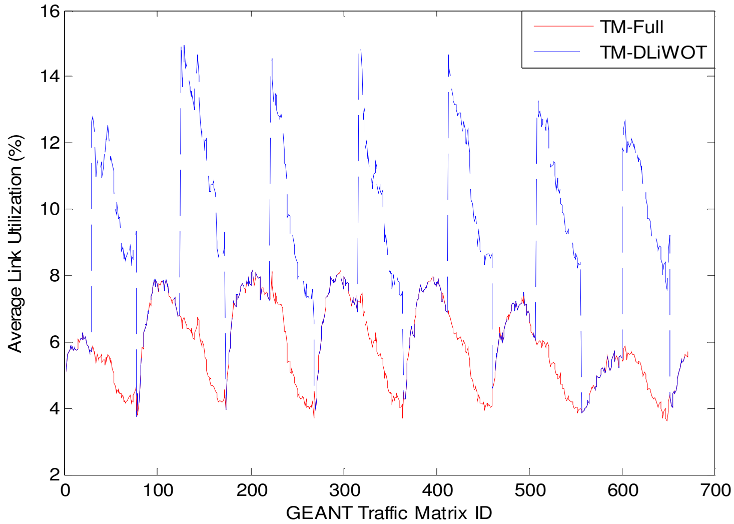

Fig. 3. ALU performance based on "full" and "pruned topology with DLiWOT" during off peak period over 7 days.

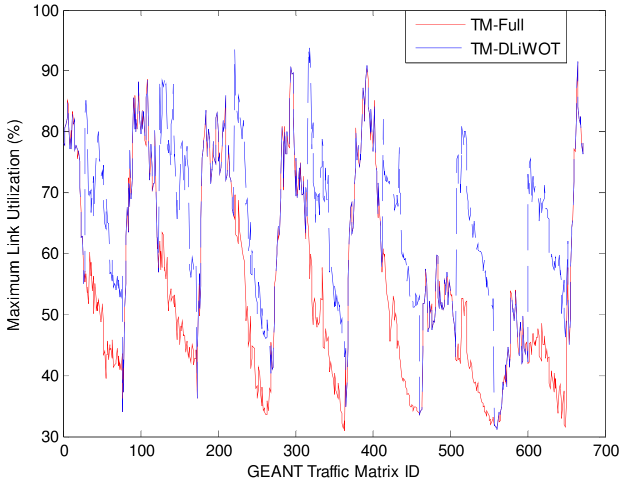

Fig. 4. MLU performance based on "full" and "pruned topology with DLiWOT" during off peak period over 7 days.

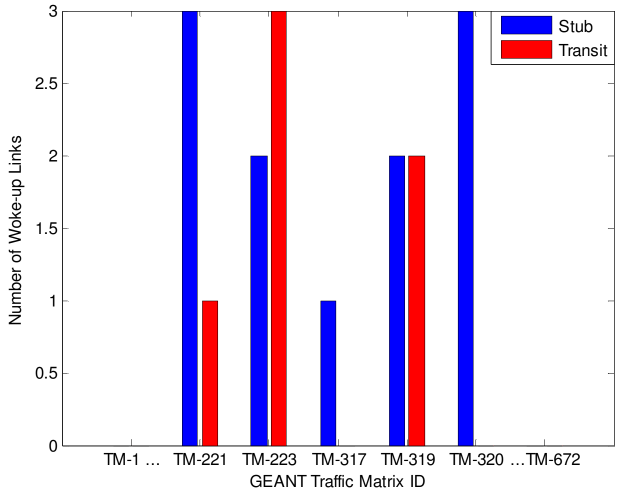

Fig. 5. Performance of DLiWOT in terms of waking up of links within a week interval.

Table 3 describes the different attributes of the pruned topology with regards to performance metrics. It shows that the reduced topology of GEANT, when applied and used subsequently by DLiWOT, leads to an ALU of about 2.5 times than that of the full topology (see also Fig. 3). This is an indication of more balanced use of network resources in our case and significant reduction in network resource underutilisation. ALU is also dependent on the threshold settings, which in our simulations was set to 95% in order to be proactive to congestion. Therefore, our algorithm is developed in such a way that it controls traffics on the network based on threshold settings, which can be tuned by a network operator depending on their preferences about proactivity to congestion and acceptable MLU levels.

On the energy savings, Table 3 shows a substantial amount of savings on a daily basis (only during off-peak periods) which is dependent on the number of sleeping links and also on their power consumption characteristics (note that the links have different power consumption characteristics; as such the energy savings are directly proportional to the power of individual links as shown in Table 2). As shown, the MLU within this period does not exceed the threshold value (see Fig. 4) despite the reduced number of active links. In this case, once the network MLU reaches the threshold value, DLiWOT is immediately deployed to control such congestion and reduce MLU below the pre-defined 95% threshold. It is also important to note that during the weekends, the off peak period can be extended because of the very low traffic, meaning that an operator can apply the DLiWOT scheme for longer time periods (which can be considered as off-peak well beyond the considered here 8PM-8AM period), thereby extending even more the energy saving gains.

Table 3. Performance analysis of TM attributes for one week during the off peak period when DLiWOT is applied.

Days	**MLU (%)**	**ALU (%)**	**Pef - Energy Savings (%)**
Monday	85.08	10.42	46.79
Tuesday	88.81	12.03	46.79
Wednesday	93.48	10.10	39.82
Thursday	94.00	10.22	40.87
Friday	82.18	11.12	46.79
Saturday	80.87	10.65	46.79
Sunday	75.51	10.31	46.79

6 Conclusions and Future work

In this paper, we propose a complementary link wake up algorithm that can be applied on top of any existing link sleeping optimisation scheme to cope with the existence of uncertainty and dynamic traffic conditions in real life networks. The algorithm aims to select the minimum number of sleeping links to wake up during traffic surge without causing any form of traffic disruption. This is in contrast to most works that unnecessarily sacrifice energy savings once there is traffic surge in the network or provide backup paths in the pruned topology as a proactive measure to congestion avoidance. To this end, we also answer a key research question on how to handle traffic surge without disruption. We demonstrate through our simulations that our scheme can be able to save substantial amounts of energy and is also robust to traffic dynamicity in a disruption free manner. More so, our scheme does not depend on the combination of different network platform for its operation i.e. operates purely in an

IP based platform alone. The obtained results showed significant energy savings and improved link utilisation without sacrificing network efficiency. It is a novel approach to today's network for possible adoption by ISPs whose paramount desire is to save energy without traffic disruption. This has also shown that adopting link sleeping mode is a realistic approach with no modification to the traditional IP forwarding protocols required.

In future work, we intend to investigate how we can explore putting back some links to sleeping mode after wake up so that the scheme can be applied seamlessly throughout the whole operational runtime of a network, maximising even further the opportunities for energy savings by “tracking” both increases and also decreases in network traffic demand conditions.

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