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A Novel Energy-Saving Algorithm Based on Sleeping Low-Loaded ONU for Hybrid Wireless-Optical Broadband Access Network

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Abstract—Since the access network plays the dominant role of energy consumption in the whole network, it is necessary to study the energy-efficient design on access technique. This paper aims to develop the green Hybrid Wireless-Optical Broadband Access Network (HWOBAN) by sleeping low-loaded Optical Network Units (ONUs) as much as possible to save the energy. Correspondingly, a heuristic approach, Energy-saving Algorithm based on Sleeping Low-loaded OUNs (EASLO), is proposed in our paper. In EASLO, most of traffic has higher probability to be carried by the currently active ONUs through dynamic energy-awareness mechanism, so that the higher resource utilization of ONUs can be achieved. Meanwhile, in order to improve the energy efficiency, we can sleep low-loaded ONUs, each of which can satisfy the conditions of traffic rerouting, and then transfer the residual traffic on these sleeping ONUs into the other active ones. The simulation results show that, our EASLO method has better performance of energy savings than traditional method.

Keywords- Hybrid wireless-optical broadband access network; energy savings; ONU sleeping; rerouting; energy awareness

1. Introduction

In recent years, the emergence of augment multi-media applications has made a severe challenge for designing the “last-mile” broadband access network. “Low expenditure”, “high capacity” and “promising flexibility” have become the new objectives for developing the future broadband access technology [1]. The optical access network based on PON (Passive Optical Network) can provide higher bandwidth but still remains cost-prohibitive. Although the wireless-access network can achieve a cost-effective solution and support mobile surfing, the limited bandwidth provision is rather unacceptable for users. Therefore, the Hybrid Wireless-Optical Broadband Access Network (HWOBAN) is proposed and gains increasing attentions in the worldwide research community [2-6]. The HWOBAN is a novel hybrid access network with the objective of merging advantages of optical backhaul (e.g., high capacity and huge bandwidth, etc) and wireless front-end (cost savings and promising flexibility).

Meanwhile, with the increase of global greenhouse effect and the growth of energy shortage, the energy savings with low carbon emission has become the focus and consensus within the whole world. With regard to the network, especially for its broadband access segment, the increasing size and the augment number of applications have caused the waste of energy and huge carbon emission. Therefore, the efforts on reducing energy consumption and “carbon footprint” have become one of the key issues in HWOBAN.

Currently, although many energy-efficient solutions for optical fiber or wireless-access network were proposed [7-10], these strategies for reducing energy consumption in traditional access networks can not be directly utilized in HWOBAN, due to its novel features. It is highly desirable to propose the effective energy management schemes for HWOBAN [11, 12]. Correspondingly, we develop energy-aware techniques based on putting ONUs to the sleep state for green HWOBAN.

2. Problem Statements

2.1 HWOBAN Architecture

HWOBAN is the novel access network architecture with an optimal combination of a wireless Mesh front-end and an optical backhaul, as shown in Fig. 1. There are three major techniques that have been employed for wireless-access networks, that is, Wireless Fidelity (WiFi), Worldwide Interoperability for Microwave Access (WiMax), and Cellular Network. The most dominant one in optical access technologies is PON. The front-end of HWOBAN is essentially a multi-hop Wireless Mesh Network (WMN) with several wireless routers. The PON segment of HWOBAN starts from the Central Office (CO), in which multiple Optical Line Terminals (OLTs) are deployed. The multiple ONUs are driven by the corresponding splitter-connected OLT. Each ONU supports several wireless routers, among which, the wireless routers directly-connected with ONU are called Gateways and the other ones provide access services for wireless end-users. Inversely, when an end-user wants to send a packet, it sends the packet to its nearest wireless router, then this wireless router delivers the packet to any of the gateways followed by multi-hop approach, and finally, the packet arrives at the Internet through PON.

2.2 Network Model

The physical topology of HWOBAN can be denoted as G={V,E}, where V and E are the sets of nodes and wireless links, respectively; $V = V_{wr} \cup V_{onu}$, in which V_{wr} and V_{onu} represent the sets of wireless router nodes and ONU/Gateway nodes, respectively; $E = E_{wl} \cup E_{o/w}$, in which E_{wl} and $E_{o/w}$ represent the sets of links between two front-end wireless routers and links between ONU/Gateway and wireless router, respectively; In this paper, we only consider the routing and bandwidth assignment for upstream traffic, the routing algorithm is $Dijkstra's$, and the required capacity of each wireless end-user demand is one unit of bandwidth (i.e., 1Mbps). Each ONU/Gateway node is assumed to have the functions of dynamic energy-awareness, sleep/awake transferring and traffic rerouting as shown in Fig. 2. The other important notations, variables and parameters are introduced in the following.

ONU_n : The n^{th} ONU/Gateway (i.e., ONU) node, $1 \le n \le |V_{onu}|$.

WR_m : The m^{th} wireless router node, $1 \le m \le |V_{wr}|$.

S: The first-hop wireless node (i.e., source node) of the currently-arriving wireless end-user demand, $s \in V_{wr}$.

d^n_{onu} : The destination ONU node numbered n, $d^n_{onu} \in V_{onu}$, $1 \le n \le |V_{onu}|$.

AT : The total number of arrived wireless end-user demands.

$T_k\left(s, d^n_{onu}\right)$: The k^{th} wireless end-user demand from source node s to the destination node d^n_{onu}, $1 \le k \le AT$ and k is an integer.

$P_s^{d^n_{onu}}$: The eligible routing path from source node s to the destination node d^n_{onu}.

$WL_{i,j}^{s,d^n_{onu}}$: The wireless link consumed by $P_s^{d^n_{onu}}$ between node i and node j, $WL_{i,j}^{s,d^n_{onu}}$, $i,j \in V$.

$C_{i,j}^{s,d^n_{onu}}$: The total available capacity (measured in Mbps) of the wireless link $WL_{i,j}^{s,d^n_{onu}}$.

$RB_{i,j}^{s,d^n_{onu}}$: The residual available capacity (measured in Mbps) of the wireless link $WL_{i,j}^{s,d^n_{onu}}$.

TC_{onu} : The total capacity (measured in Mbps) of each ONU.

$T^n_{open\_close}(T_a, T_b)$: The pair of time variables (T_a, T_b) that real-time records the time of two different and continuous operations (sleep/awake) on ONU_n, and $Ta > Tb$.

$T^n_{onu\_close}$: The time variable that real-time records the time of sleeping ONU_n.

$T^n_{onu\_open}$: The time variable that real-time records the time of waking up ONU_n.

ad^n_{onu} : The time variable that records the duration of awake state for ONU_n, $ad^n_{onu} = ad^n_{onu} + \left(T^n_{onu\_close} - T^n_{onu\_open}\right)$, $T^n_{onu\_close}, T^n_{onu\_open} \in T^n_{open\_close}\left(T^n_{onu\_close}, T^n_{onu\_open}\right)$ and $1 \le n \le |V_{onu}|$.

sd^n_{onu} : The time variable that records the duration of sleep state for ONU_n, $sd^n_{onu} = sd^n_{onu} + \left(T^n_{onu\_open} - T^n_{onu\_close}\right)$, $T^n_{onu\_close}, T^n_{onu\_open} \in T^n_{open\_close}\left(T^n_{onu\_open}, T^n_{onu\_close}\right)$ and $1 \le n \le |V_{onu}|$.

WC_{onu}^{n}: The load variable that real-time records the current working load of ONU_n, $1 \le n \le |V_{onu}|$;

FC_{onu}^{n} : The load variable that real-time records the current residual available capacity of ONU_n, $1 \le n \le |V_{onu}|$.

$OPEN_{onu}^{n}$: The Boolean variable that real-time records the current state of ONU_n, $1 \le n \le |V_{onu}|$. $OPEN_{onu}^{n} = 1$ if the state of ONU_n is or turned to awake; otherwise $OPEN_{onu}^{n} = 0$.

HW: The upper bound of working load on each ONU, $\forall HW < TC_{onu}^{n}$. Introducing this notation is to avoid the bottleneck of overloaded ONU.

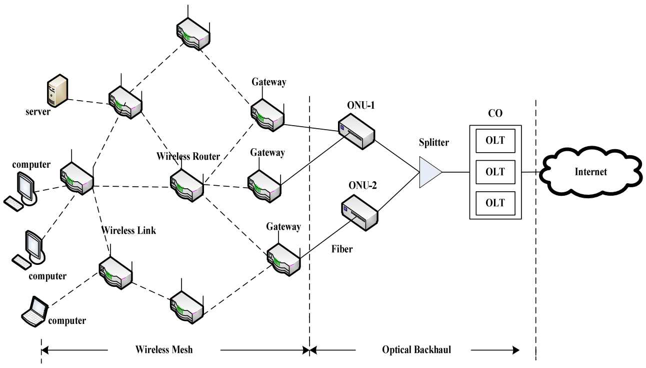

Figure 1. The HWOBAN architecture

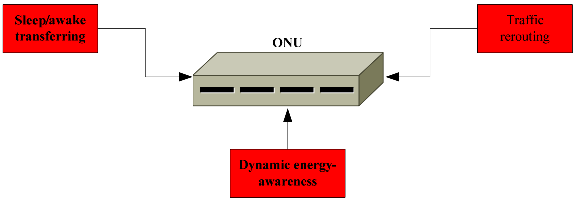

Figure 2. The identified ONU

S_{avai_onu}: The candidate set of available destination ONUs. Only the eligible ONU_n $(\forall n, 1 \le n \le |V_{onu}|)$ that satisfies $WC_{onu}^{n} < HW$ can be put into S_{avai_onu} before we compute the routing path for the currently-arriving wireless end-user demand, and $|S_{avai\_onu}| \le |V_{onu}|$.

LW: The lower bound of working load on each ONU. If $WC_{onu}^{n} < LW$ $(\forall n, 1 \le n \le |V_{onu}|)$, the FC_{onu}^{n} amount of traffic would be transferred into another ONU in S_{avai_onu}.

P_{onu}^{on}: The power (measured in Walt) of each ONU with the state of awake.

P_{onu}^{off}: The power (measured in Walt) of each ONU with the state of sleep.

$|\delta|$: The number of elements in set δ.

3. Identified Onu

The identified ONU is shown in Fig. 2. It mainly has three new functions of energy-awareness, sleep/awake transferring and traffic estimation [13, 14] based rerouting.

***Dynamic energy-awareness*:** Initialize the values of HW and LW for each ONU, adaptively acquire the information of working load for each ONU orderly in set V_{onu} and put the eligible ONUs, each of which satisfies $WC_{onu}^{n} < HW$ $(1 \le n \le |V_{onu}|$ and the ONU_n with $WC_{onu}^{n} = 0$ is also considered), into S_{avai_onu}. We sort all of eligible ONUs in S_{avai_onu} according to working load in the descending order and decide the first ONU from updated S_{avai_onu} as the destination ONU, i.e., d_{onu}^{m}, $(\forall m, 1 \le m \le |V_{onu}|)$. If $OPEN_{onu}^{m} = 0$, we will wake up ONU_m, let $OPEN_{onu}^{m} = 1$, record $T_{onu\_open}^{m}$ and put $T_{onu\_open}^{m}$ into the corresponding $T_{open\_close}^{n}(T_a, T_b)$. Therefore, deciding the destination ONU with the maximum working load by utilizing dynamic energy (load)-awareness method can realize the excessive energy consumption of information polling between OLT and ONUs. On the other hand, this method also can improve the resource utilization of active ONUs.

***Sleep/awake transferring*:** With the demands leaving network, the working load of some ONU could decrease. As mentioned above, if $WC_{onu}^{n} < LW \ (\forall n, 1 \le n \le |V_{onu}|)$, the corresponding ONU_n could be put into the sleep state. But the final state is totally dependent on the conditions of traffic rerouting for this ONU_n. If the conditions can be satisfied, we can sleep this ONU_n after transferring its residual traffic to another active one. Then we need to record $T_{onu\_close}^{n} \ (1 \le n \le |V_{onu}|)$ for this ONU_n and put $T_{onu\_open}^{n}$ into the corresponding $T_{open\_close}^{n}(T_a, T_b)$.

***Traffic rerouting*:** The conditions of traffic rerouting for the tested $ONU_m \ (\forall 1 \le m \le |V_{onu}|)$ is described as follows:

Condition (a): $|S_{avai\_onu}| \times (TC_{onu} - HW) + FC_{onu}^{m} \le \sum FC_{onu}^{n}$, , $n = \{1, 2, \ldots, |S_{avai\_onu}|\} \ and \ n \ne m$, which means that the total residual available bandwidth from all of active ONUs must be enough for carrying the residual traffic on ONU_m; **Condition (b):** Decide the new destination ONU for each residual demand on ONU_m orderly, according to the method mentioned in subsection 3.1. Then, all of rerouting paths for FC_{onu}^{m} demands on ONU_m must be successfully found. If both conditions (a) and (b) can be satisfied, release the resource of consumed wireless links and ONU_m, and allocate rerouting bandwidth for FC_{onu}^{m} demands ; otherwise, the traffic rerouting is refused and ONU_m can not be turned into the sleep state.

4. Illustration of Easlo

The OLT is assumed to be always active and the corresponding energy consumption is not considered in this paper. In the following, we take an illustration to analyze the consumed energy during one unit of time (i.e., consumed power) between our EASLO and the traditional Minimizing Hop Routing Algorithm (MHRA). In Fig. 3, $V_{onu} = \{ONU_1, ONU_2, ONU_3, ONU_4\}$, the numbers labeled in ONU_n, $n = \{1, 2, 3, 4\}$, denote the current working load WC_{onu}^{n}, and $WC_{onu}^{1} = 80$, $WC_{onu}^{2} = 4$, $WC_{onu}^{3} = 21$, $WC_{onu}^{4} = 5$. The parameter settings in this example are as follows: HW=80, LW=5, TC_{onu}=100, $P_{onu}^{on} = 10W$ and $P_{onu}^{off} = 1W$.

The Fig. 3 (a) shows the example of traditional wireless front-end routing and resource assignment method, MHRA. For the wireless end-user demand $T_k(WR_2, d_{onu}^{n})$ that arrives at the first-hop wireless router currently, the candidate set $S_{avai\_onu} = \{ONU_2, ONU_3, ONU_4\}$ since $WC_{onu}^{1} + 1 > 80$. The MHRA uses the first-fit method in S_{avai_onu} to decide the destination ONU $d_{onu}^{n} = d_{onu}^{2}$, then computes the shortest path $P_{WR_2}^{d_{onu}^{2}}$, with consuming the wireless links $WL_{WR_2,WR_3}^{WR_2,d_{onu}^{2}}$, $WL_{WR_3,WR_5}^{WR_2,d_{onu}^{2}}$ and $WL_{WR_5,ONU_2}^{WR_2,d_{onu}^{2}}$, as well as let $RB_{WR_2,WR_3}^{WR_2,d_{onu}^{2}} \rightarrow RB_{WR_2,WR_3}^{WR_2,d_{onu}^{2}} - 1$, $RB_{WR_3,WR_5}^{WR_2,d_{onu}^{2}} \rightarrow RB_{WR_3,WR_5}^{WR_2,d_{onu}^{2}} - 1$, $RB_{WR_5,ONU_2}^{WR_2,d_{onu}^{2}} \rightarrow RB_{WR_5,ONU_2}^{WR_2,d_{onu}^{2}} - 1$ and $WC_{onu}^{2} \rightarrow WC_{onu}^{2} + 1 = 5$. Once a unit of traffic leaves the network from ONU_4, then $WC_{onu}^{4} \rightarrow WC_{onu}^{4} - 1 = 4$. However, even if $WC_{onu}^{4} < LW$, the ONU_4 can not be turned into the sleep state yet, due to the lack of effective sleep and rerouting mechanisms in MHRA. Finally, the total consumed energy during one unit of time followed by MHRA is $TP_{onu} = 4 \cdot P_{onu}^{on} = 40J$.

Considering the same case of demand arriving and leaving in Fig. 3 (a), the example of wireless front-end routing and resource assignment in our EASLO is shown in Fig. 3 (b). If the demand carried by ONU_2 in Fig. 3 (a) leaves the network from ONU_2 in Fig. 3 (b), where one unit of traffic also leaves the network from ONU_4, then $WC_{onu}^{2} < LW$ and $WC_{onu}^{4} < LW$. Therefore, our EASLO transfers the residual traffic on these two ONUs to the ONU_3 so that $WC_{onu}^{2} = WC_{onu}^{4} = 0$, sleeps ONU_2 and ONU_4, and updates $WC_{onu}^{3} \rightarrow WC_{onu}^{3} + 4 + 4 = 29$. Correspondingly, the destination ONU $d_{onu}^{n} = d_{onu}^{3}$ since ONU_3 has the maximum working load in candidate set $S_{avai\_onu} = \{ONU_2, ONU_3, ONU_4\}$. Thus, for the wireless end-user demand $T_k(WR_2, d_{onu}^{3})$, we can compute the shortest path $P_{WR_2}^{d_{onu}^{3}}$ with consuming the wireless links $WL_{WR_2,WR_3}^{WR_2,d_{onu}^{2}}$, $WL_{WR_3,WR_5}^{WR_2,d_{onu}^{2}}$, $WL_{WR_5,WR_6}^{WR_2,d_{onu}^{2}}$ and $WL_{WR_6,ONU_3}^{WR_2,d_{onu}^{2}}$, let $RB_{WR_2,WR_3}^{WR_2,d_{onu}^{2}} \rightarrow RB_{WR_2,WR_3}^{WR_2,d_{onu}^{2}} - 1$, $RB_{WR_3,WR_5}^{WR_2,d_{onu}^{2}} \rightarrow RB_{WR_3,WR_5}^{WR_2,d_{onu}^{2}} - 1$, $RB_{WR_5,WR_6}^{WR_2,d_{onu}^{2}} \rightarrow RB_{WR_5,WR_6}^{WR_2,d_{onu}^{2}} - 1$, $RB_{WR_6,ONU_3}^{WR_2,d_{onu}^{2}} \rightarrow RB_{WR_6,ONU_3}^{WR_2,d_{onu}^{2}} - 1$, and $WC_{onu}^{3} \rightarrow WC_{onu}^{3} + 1 = 30$. Finally, the total consumed energy during one unit of time followed by our EASLO is $TP_{onu} = 2 \cdot P_{onu}^{on} + 2 \cdot P_{onu}^{off} = 22J$, which can save $18J$ energy compared with the traditional MHRA method. The improvement ratio of energy savings followed by our EASLO in this example can be up to 45%. And the longer sleep duration, the better performance of energy savings in our EASLO.

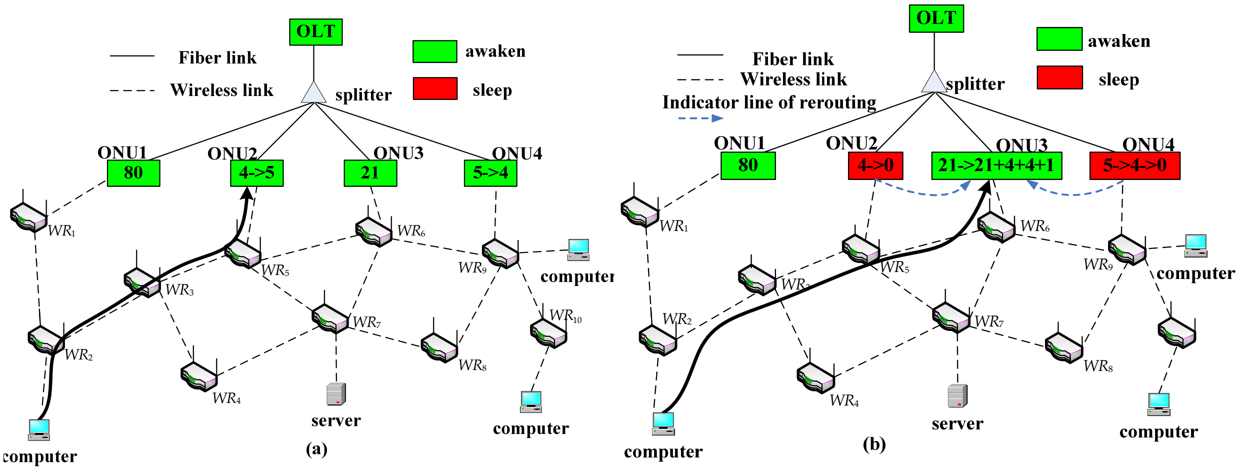

Figure 3. The illustration of our EASLO

We can see that, the time complexity of our EASLO is mainly dependent on two phases of destination ONU decision and traffic rerouting. For each demand at the worst case, their time complexities are mainly dependent on the capacity of candidate set S_{avai_onu} and the times of running $Dijkstra's$, respectively. Therefore, the time complexities of these two phases are approximately $|S_{avai\_onu}|$ and $FC_{onu}^{m} \times |S_{avai\_onu} - \{ONU_m\}|^2$, where FC_{onu}^{m} $(1 \le m \le |S_{avai\_onu}|)$ denotes the rerouted traffic on ONU_m.

5. Peformance Evaluation

The 24-node (20 wireless router nodes and 4 ONU nodes are included) network topology tested in simulations is shown in Fig. 4. We simulate a dynamic network environment with the assumptions that wireless end-user demands arrive according to an independent Poisson process with arrival rate β and the demands' holding times are negatively exponentially distributed $1/\mu$, i.e., the network load is β/μ Erlang. In simulations, we set μ to 1. All simulation results are obtained by generating up to 10^4 demands. The parameter settings are as follows: TC_{olt} =1Gbps, TC_{onu} =100Mbps, $C_{WL_{i,j}^{s,d_{onu}^{n}}}$ =54Mbps, P_{onu}^{on} =10w, and P_{onu}^{off} =1w. In addition to this, the values of HW and LW are respectively obtained the 80% and 5% of TC_{onu}. The compared performances between our EASLO and the traditional MHRA are in the following.

$$AEC = \frac{P_{onu}^{on}\left(\sum_{i=1}^{n} ad_{onu}^{i}\right) + P_{onu}^{off}\left(\sum_{i=1}^{n} ad_{onu}^{i}\right)}{T_s} \tag{1}$$

$$SDR = \frac{\left(\sum_{i=1}^{n} sd_{onu}^{i}\right)}{4S_c} \tag{2}$$

$$APL = \frac{\sum_{k=1}^{T_s} L_k}{T_s} \tag{3}$$

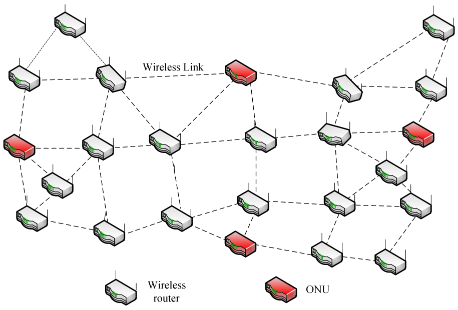

Figure 4. The test network

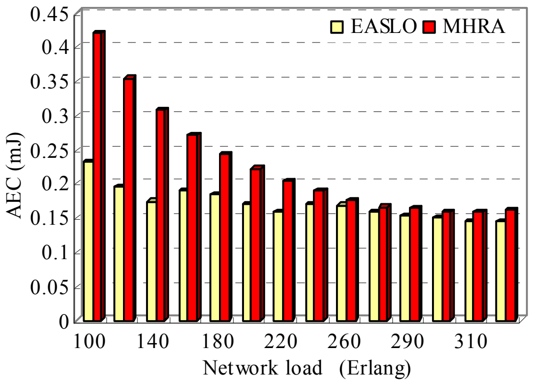

Figure 5. The performance of AEC in EASLO and MHRA

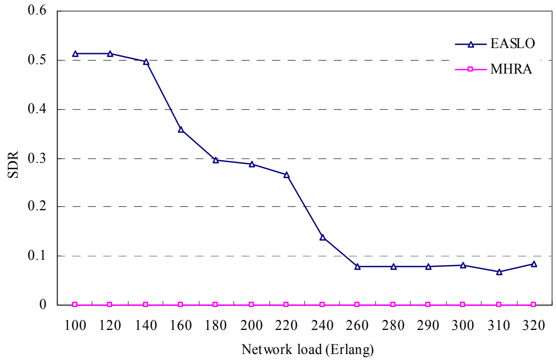

Figure 6. The performance of SDR in EASLO and MHRA

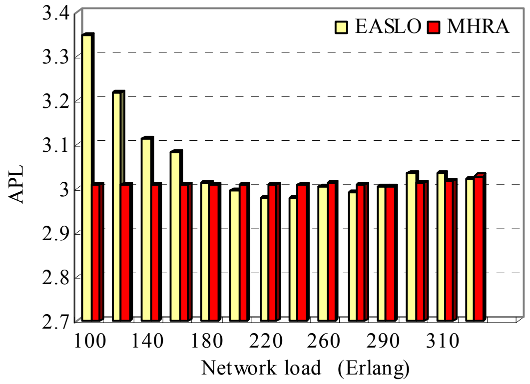

Figure 7. The performance of APL in EASLO and MHRA

The Average Energy Consumption (AEC) is defined in Eq. (1) where T_s represents the number of accepted wireless end-user demands; the Sleep Duration Ratio (SDR) of ONU is defined in Eq. (2) where S_C is the simulation time; the Average Path Length (APL) is defined in Eq. (3) where L_k denotes the path-length of the k^{th} wireless end-user demand.

The performance of AEC is compared between EASLO and MHRA with the different network load in Fig. 5. The lower AEC means the less energy consumed by each accepted wireless user-end demand. The simulation results show that, the AEC of EASLO is lower than that of MHRA. The reason for this is that, followed by the three new mechanisms, dynamic energy-awareness, sleep/awake transferring and traffic rerouting, the energy consumed by ONUs can be reduced in our EASLO.

The performance of SDR is compared between EASLO and MHRA with the different network load in Fig. 6. The bigger SDR means the lower total energy consumption. The simulation results show that, the SDR of EASLO is absolutely bigger than that of MHRA. The reason for this is that, our EASLO can turn the low-loaded ONUs into the sleep state, which can save more energy. Furthermore, under the case of lower network load, our EASLO can keep about half of ONUs in the sleep state. While with the network load increasing, the

SDR of EASLO becomes lower. Due to the lack of effective sleep mechanism, the SDR of MHRA is always zero.

The performance of APL is compared between EASLO and MHRA with the different network load in Fig. 7. The simulation results show that, under the case of lower network load, the APL of EASLO is slightly higher than that of MHRA while with the network load increasing, the APLs of EASLO and MHRA are basically equal. This is because that, under the case of lower network load, the working load of the most ONUs is usually very low, then we have the higher probability of turning ONUs into the sleep state at the slight cost of longer path-length. However, with the network load increasing, the probability of rerouting traffic becomes lower and the corresponding APL of EASLO tends to be that of MHRA.

6. Conclusion

This paper proposed a novel energy-saving algorithm called EASLO for green hybrid wireless-optical broadband access network. In our EASLO, three new mechanisms were introduced. First, the energy (load)-awareness mechanism was utilized to decide the destination ONU with the maximum working load in candidate set, so that the resource utilization of ONU can be improved by holding the traffic as much as possible on ONUs with higher working load; second, the sleep/awake transferring mechanism was used to check whether one ONU can be turned into the sleep state or not, by setting the upper/lower bounds of working load for each ONU; finally, the traffic rerouting mechanism was applied to rerouting the residual traffic on the ONU that satisfies the conditions of traffic rerouting. The simulation results showed that our EASLO outperformed MHRA method on energy savings at the slight cost of average path-length. The corresponding improvement ratio can be up to around 20%.

7. Acknowledgement

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