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Joint Wireless and Optical Power States Scheduling for Green Multi-radio Fiber-Wireless Access Network

Pengchao Han, Lei Guo, Yejun Liu, Jian Hou, Xu Han

Abstract*—Due to the massive deployment of electrical network devices, Fiber-Wireless (FiWi) access network has to suffer from the challenge of high energy consumption. With the ever-increasing eager for green communication infrastructure, the issue of high energy consumption may become one of the major barriers for the advance of FiWi access network. Previous works proposed for green FiWi access network cover three aspects, including the optimized deployment of network devices such as Optical Network Units (ONUs), the energy-efficient bandwidth allocation of ONUs with QoS guarantee, and the dynamic power states scheduling of ONUs (i.e., active/sleep) according to their traffic profile. However, these works did not take the energy-saving design of wireless subnetwork into account simultaneously. In fact, when some ONUs in the optical subnetwork are switched into sleep states, part of the radio interfaces originally forwarding traffic to the sleep ONUs would be idle or low-loaded. This provides a potential opportunity for energy-saving in wireless subnetwork by switching off the idle or low-loaded radios. This paper focuses on the design of green multi-radio FiWi access network by integrating the energy-savings of optical and wireless subnetworks. To support the energy-efficient design, the new power states are defined for ONUs and radios, respectively. Aiming at dynamic traffic profile, the heuristic algorithms are proposed for the energy saving of integrated wireless front-end and optical back-end of FiWi access network. First, the Energy-saving Algorithm with ONU Sleep mechanism (EAS) is proposed to dynamically schedule the power states of ONUs by judging their traffic profile with load thresholds. Then, the Energy-saving algorithm based on Radios Off (ERO) is proposed to reconfigure the topology of wireless subnetwork by controlling the power states of radios dynamically. Moreover, wireless rerouting is employed in both EAS and ERO to guarantee the QoS provisioning ability of network. Finally, a comprehensive energy-saving scheme called EE is proposed by combining the EAS and ERO algorithms strategically. Simulation results show that with the reasonable setting of parameters, the proposed EE scheme can save the energy of 33.14% to 64.35% and 8.56% to 36.42% in a wide range of traffic load compared to the No-energy-saving and QoS-aware energy-saving scenarios, respectively.

***Index Terms*—Fiber-Wireless access network, energy-saving, ONU sleep, radio off, routing.**

I. INTRODUCTION

PASSIVE Optical Network (PON) and Wireless Mesh Network (WMN) are two of the dominant broadband access networks today. Because of the high bandwidth capacity of optical fiber and the tree-like topology, PON can provide high bandwidth for data application with a much long transmission distance. The passive transmission of optical signal in PON ensures its high reliability without electromagnetic interference. However, the deployment cost of optical fiber links in PON is expensive and cannot achieve an anytime-anywhere access. In contrast, WMN is much flexible and low-cost as a result of wireless deployment and free-licensed spectrum [1]. However, the limited bandwidth due to scarce spectrum and co-channel interference hinders the steps of WMN on the way to next-generation broadband access network [2].

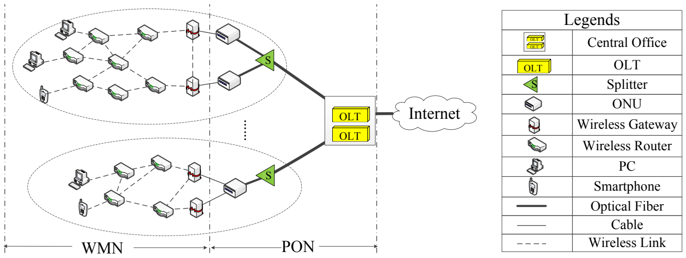

Fig. 1. Architecture of FiWi access network.

As a promising broadband access technology, Fiber-Wireless (FiWi) access network combines PON and WMN, and thus it inherits their technological advantages. A typical architecture of FiWi access network is shown in Fig. 1. The optical back-end is composed of Optical Line Terminal (OLT) locating in Central Office (CO), splitter and Optical Network Units (ONUs). The OLT can communicate with one or more ONUs through the splitter. The wireless gateways which are equipped with both wired and radio interfaces are responsible to connect an ONU with one or more wireless routers in WMN. The mesh topology of WMN makes sure that the end-users (e.g., PC and smartphone) can communicate with more than one ONUs, which contributes to the robustness of FiWi access network. The simplest architecture of WMN in the front-end is the flat deployment of wireless routers, each of which is equipped with a single radio [3]. With the increasing demand for network capacity, as well as the urgent need for mitigating bandwidth bottleneck between wireless and optical subnetworks, the use of multi-radio WMN in FiWi access network is gaining the widespread popularity [3].

According to an up-to-date survey [4]–[6], the energy consumption of global networks accounts for about 8% of the total energy consumption, and the proportion will reach up to 20% by 2020. Particularly, access network contributes more than 70% to the total network energy consumption. High energy

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Pengchao Han, Lei Guo, Yejun Liu, Jian Hou and Xu Han are with the School of Computer Science and Engineering, Northeastern University, Shenyang, P. R. China.

Correspondence to: Lei Guo (email: guolei@cse.neu.edu.cn).

consumption has become one of the primary problems for the advance of FiWi access network in future. As a result of the dynamic network load over time, the traditional network with fixed topology exhibits a lot of disadvantages. For example, network topology is traditionally designed according to peak traffic profile such that many network devices would become idle in the presence of low-load hours, which leads to the underutilized network resource and energy waste. Therefore, there is a potential opportunity for network energy-saving by dynamically switching the devices with low or zero load into low-power states.

Some works have been carried out to investigate the energy-saving of PON or FiWi access network by dynamically switching the ONUs into sleep states. When an ONU is sleeping, it works at the level of low-power and thus reduces energy consumption. There have been some low-power states proposed for the energy-saving of ONUs such as power shedding, doze, deep sleep, and fast sleep. These low-power states allow ONUs to save different portion of energy by shutting down their different electrical components. However, most of the existing low-power states of ONUs just consider the shutdown of transmitters/receivers at OLT side regardless those at gateway side. It is undoubted that shutting down the gateway-side transmitters/receivers of the sleeping ONUs will contribute to further energy-saving.

Furthermore, most of the previous works consider the energy-saving of optical subnetwork by scheduling the power states of ONUs or optimizing the placement of ONUs according to the traffic load. However, they remain less touched the issue of energy-saving in wireless subnetwork. In fact, when some ONUs in the optical subnetwork are switched into sleep states, part of the radio interfaces previously forwarding traffic to the sleep ONUs would be idle or low-loaded, especially in the scenario of multi-radio FiWi access network. Thus, there exists an unnecessary energy waste in the wireless subnetwork when the ONU sleep mechanism is considered alone for the design of green multi-radio FiWi access network. A promising solution for the energy consumption issue of multi-radio FiWi access network is to integrate the wireless and optical energy-savings.

In this paper, we focus on the design of green multi-radio FiWi access network and an energy-saving scheme is proposed to jointly schedule the power states of the ONUs and radio interfaces. First, the mathematical model is formulated for the problem of designing green multi-radio FiWi access network. Then, the heuristic algorithms are also proposed to support the dynamic traffic profile. For the energy-saving of PON, we propose a new low-power state for ONU sleep in which both OLT-side transmitters and wireless gateway-side transmitters/receivers can be turned off according to the traffic load. Based on the new ONU sleep state, an Energy-saving Algorithm with ONU Sleep mechanism (EAS) is further proposed to determine the power states of all ONUs by employing a pair of load thresholds. Meanwhile, for the energy saving of WMN, each radio interface is also configured with two power states, i.e., on and off. While a radio is operated in off state, its transmitter and related components (e.g. amplifier) will be powered off. Thus, any radio can switch into off state only if there is not any traffic on it. However, the receiver of an off-state radio will be always maintained on to receive the state-switching command from OLT. Moreover, each radio also has the ability of requiring other radios to turn on their transmitters while there is not any feasible path for a new demand. It should be noticed that what we emphasize is the power saving state of wireless radio interface as it is admitted that the energy it consumes represents 50% to 80% of the overall consumption of a wireless node [7]. Other modules in wireless router such as power generation module, processor and controller module [8] will not be influenced. An Energy-saving algorithm based on Radios Off (ERO) is proposed to centrally control the power states of radios. To guarantee the QoS provisioning ability of network, it is specified in ERO that the active radios should have enough capacity to carry the existing traffic over the whole network.

In summary, an effective scheme called EE is proposed for the comprehensive energy-saving of multi-radio FiWi access network by implementing these two algorithms (EAS and ERO) interactively.

The remainder of this paper is organized as follows. In Section II, the related works and existing challenges are reviewed and analyzed. Then, the mathematical models of the optimization problems about the design of green multi-radio FiWi access network are formulated in Section III. The heuristic solutions for the optimization problems are proposed in Section IV. The simulation results and analysis are shown in Section V. Finally. Section VI concludes our work.

II. RELATED WORKS

Some low-power states have been proposed for the energy-saving of ONUs [9], [10]. As shown in Table I, the ONU power shedding state allows manager to shut down the unused User Network Interfaces (UNIs) manually while keeping transmitters and receivers always on. According to an ITU-T study, power shedding can save over 70% of active power for a typical North-American ONU while the size of the backup battery can be reduced by more than 50% [9]. The ONU doze state will shut down the non-essential function modules and OLT-side transmitters while keeping receivers on. Of course, the communication with downstream devices (from ONUs to wireless routers) remains unaffected. When an ONU is in deep sleep state, most of its function modules will be switched off including its OLT-side transmitter and receiver, while just some basic function modules remain optionally active such as the activity detection and some local timers. Thus, the ONU in deep-sleep state can only be activated by means of its local trigger mechanism. The deep sleep state is highly energy-efficient. However, it is complicated and suffers from the risk of QoS decline. The ONU fast sleep state contains two stages called active stage and deep sleep stage in each fast sleep cycle, which is less flexible but easily operated compared to deep sleep state.

Based on the above power states of ONUs, some related works have been carried out to investigate the energy-aware design of FiWi access network [11]–[16]. There are mainly three aspects about the building of green FiWi access

TABLE I

CHARACTERISTICS OF POWER STATES OF ONUS IN PON

ONU Power state	Other non-essential function modules except transmitter/ receiver	OLT-side transmitter	OLT-side receiver	Wireless gateway-side transmitter/ receiver	trigger for sleep	trigger for active
Active	on	on	on	on	N/A	N/A
Power shedding	off (only UNIs)	on	on	on	❶/❷/❸	❶/❷/❸
Doze	off	off	on	on	❷/❸	❷/❸
Deep sleep	off	off	off	on	❷/❸	❸
Fast sleep	Being in active or deep sleep state periodically				❸	❸

❶ denotes the state of ONU can be switched manually, ❷ denotes the ONU can be activated or switched into sleep state according to OLT command, and ❸ denotes the state of ONU can be controlled through its local timer.

network. The first aspect pays attention to the design of network topology by optimizing the deployment of network devices and implementing network topology reconfiguration periodically. For example, Shalini Raavi et al. [11] focused on the placement of energy-saving devices in FiWi access network. With the objective of minimizing the deployment cost of wireless routers and ONUs, the authors compared and analyzed three feasible approaches, i.e., re-configuration approach, peak-design approach and time-aware approach. The results demonstrated that time-aware approach was the best solution, in which a time factor was introduced to adjust to the variation in traffic profile during the day. Compared with other two approaches, the time-aware approach decided the number of routing devices over time and provided a better solution for the problem of equipment placement in the network while satisfying the coverage and capacity constraints. The time-aware approach showed that a large portion of energy was possible to be saved if energy factor was taken into account during network equipment placement. However, all these approaches are independent of the energy-saving mechanism in the stage of network operation when the traffic arrives randomly. In practice, energy-saving design could also be implanted into the stage of network operation to acquire higher energy efficiency, e.g., through energy-aware resource allocation and reasonable scheduling of ONU power states.

The second aspect emphasizes the QoS guarantee by using the energy-efficient bandwidth allocation, in which the power states of ONUs are controlled together with the setting of their transmission windows. Thus, the sleep duration that each ONU can enjoy is relevant to its transmission window size. J. Coimbra [13] focused on improving the energy efficiency of FiWi access network by exploiting the path diversity of wireless mesh subnetwork. A network formation game model was developed in which the network structure with complete connection stability was first proposed and then a Dynamic Network Formation (DNF) scheme was proposed. Simulation results showed that DNF could reduce the probability of traffic congestion and achieve an energy-efficient network by prolonging the duration of ONU sleep. Burak Kantarci [14] researched the service quality of energy-efficient bandwidth allocation scheme in long-reach FiWi access network. A two-stage buffering and burst-mode reporting approach was proposed and named as ELEGANT-DBA++ due to its enhanced delay performance and energy-saving advantage. Thanks to the two-stage buffering mechanism, ONUs could spend more time in the sleep mode. Furthermore, ELEGANT-DBA++ could achieve shorter ONU buffers due to the burst-mode reporting mechanism. Thus, the ELEGANT-DBA++ approach not only enabled the energy-saving but also reduced maximum packet delay for both FTTx (Fiber To The x) and wireless users. It is worth mentioning that, due to the flexibility of bandwidth allocation, most of the previous works are effective in reducing energy consumption while guaranteeing QoS for users. However, this kind of energy-saving approach is computationally complex because of the heterogeneous characteristics between wireless front-end and optical back-end. Furthermore, the difference of resource allocation between wireless and optical subnetworks also limits the efficiency of energy-saving.

The last aspect attempts to dynamically control the power states of ONUs according to their traffic profile. An ONU with low or zero load can be switched into sleep state and its remaining traffic can be wirelessly rerouted into other active ONUs at the cost of negligible QoS decline. G. Schtz [15] proposed a two-step approach to design QoS-aware energy-efficient FiWi access network. The first step aims to obtain a better QoS of FiWi access network by determining the more appropriate values for the flow-related variables. The second step optimizes the sleep mode scheduling under the constraint of packet delay. Through the optimal sleep mode scheduling, the network energy consumption was significantly reduced while the packet delay was kept at an acceptable level. Simulation results showed that the proposed approach was able to reduce energy consumption with lower average packet delay and without sacrificing network utilization. P. Chowdhury [16] and his partners emphasized the problem of high energy-consumption of ONUs. They proposed the coordinated ONU shut-down algorithm and the energy-aware routing algorithm for FiWi access network. These algorithms can effectively reduce the network energy consumption by first rerouting traffic and then switching ONUs into sleep states while satisfying the path delay constraint. However, most of these algorithms consider only the energy-saving design of PON, but ignore the energy efficiency of WMN in which a large number of radio interfaces would be idle when PON operates in the energy-saving mode. As for wireless mesh router, typical power levels of wireless radio is 3.763W in on state and 0.957W in off state [17]. The large scale deployment of wireless routers provides opportunity to save energy although the power levels seem to be insignificant compared to a 4G/LTE (the Fourth- generation / Long Term Evolution) eNodeB when it comes to a single off-radio energy saving. Furthermore, the characteristics of flexible resource scheduling and self-organization in WMN also provide an opportunity to save energy consumption of WMN subnetwork. Therefore, there will be a great space for further energy optimization if the energy-saving design of wireless and optical subnetworks is integrated especially in the multi-radio FiWi access network.

III. PROBLEM FORMULATION

In this section, we first introduce the notations used for the problem formulation. Then, an overview of green multi-radio

FiWi access network is given. Last, we formulate mathematically the problems in the design of green multi-radio FiWi access network including traffic routing, scheduling of ONU power states and scheduling of radio power states.

A. Notations

- $G(V,E)$: network graph. V denotes the set of nodes including OLT, splitter, ONUs, wireless gateways and wireless routers, where $v_i \in V$ denotes the node indexed by i, and V_O, V_W and olt denote the set of ONUs, wireless routers (including gateways) and OLT respectively. E denotes the set of bidirectional edges between different nodes, where $e_{(i,j)}$ taking 1 if there exists a link $l_{(i,j)} \in E$ between v_i and $v_j (i \neq j)$ and 0 otherwise.
- $G^{'}(V^{'},E^{'})$: residual network of $G(V,E)$, in which the network devices (ONUs and wireless radios) in sleep/off state and the invalid links caused by these sleep/off devices are excluded from $G(V,E)$. Similarly, $e^{'}_{(i,j)}$ taking 1 if there exists a link $l^{'}_{(i,j)} \in E^{'}$ between v_i and $v_j (i \neq j)$ and 0 otherwise.
- N: total number of nodes in the network including OLT, splitter, ONUs, wireless gateways and wireless routers.
- N_O: total number of ONUs in PON.
- N_W: total number of wireless routers (including gateways) in WMN.
- N_R: number of radios on each wireless router.
- o_u: the uth ONU, where $u \in \{1, 2, \cdots, N_O\}$.
- w_p: wireless router (or gateway) indexed by p, where $p \in \{1, 2, \cdots, N_W\}$.
- $wr_{(p,r)}$: the rth radio of w_p where $r \in \{1, 2, \cdots, N_R\}$.
- k: index of traffic demand, where $k \in \{1, 2, 3, \cdots, K\}$ and K denotes the total number of demands.
- n^s_k: source node of the demand k.
- n^d_k: destination node of the demand k, i.e., OLT.
- b_k: bandwidth requirement of the demand k in the unit of Mbps.
- $\xi^k_{(i,j)}$: binary variable, taking 1 if the routing path of the kth demand passes $l_{(i,j)}$ $(i \neq j,\ i,j \in \{1, 2, \cdots, N\})$ and 0 otherwise.
- $C_{(i,j)}$: bandwidth capacity of $l_{(i,j)}$ in the unit of Mbps.
- $c^r_{(i,j)}$: residual bandwidth capacity of $l_{(i,j)}$ in the unit of Mbps, where $0 \leq c^r_{(i,j)} \leq C_{(i,j)}$.
- H: the constraint of path length. A path will be regarded as unreachable if its length is more than H hops.
- χ^O_u: binary variable, taking 1 if o_u is active and 0 if o_u is in sleep state.
- $\chi^W_{(p,r)}$: binary variable, taking 1 if $wr_{(p,r)}$ is switched on and 0 otherwise.
- η^O_u: current load of o_u in the unit of Mbps.
- $\eta^W_{(p,r)}$: current load of $wr_{(p,r)}$ in the unit of Mbps.
- $\{wr_{(q,s)}\} = Negb(wr_{(p,r)})$: The function returns the set of radios that are in the neighbor domain of $wr_{(p,r)}$. The domain is the set of wireless radios $wr_{(q,s)}$, where $q \in \{1, 2, \cdots, N_W\}$, $s \in \{1, 2, \cdots, N_R\}$, and the node w_q is in the transmission range of w_p. Other radios of w_p except for $wr_{(p,r)}$ is also included.
- $\gamma_{(i,j)}$: the radio of w_i that is taken by $l_{(i,j)}$ as the transmission radio interface, where $\gamma_{(i,j)} \in \{1, 2, \cdots, N_R\}$.
- W_{low}: low load threshold for ONU sleep. An ONU can be switched into sleep when its normalized traffic load is lower than W_{low}.
- W_{high}: high load threshold for activating ONU. An ONU can be activated when there is another ONU whose normalized traffic load is higher than W_{high}.
- R_{low}: low load threshold for radio off. A radio can be switched into off state when its normalized traffic load is lower than R_{low} on the basis that its load can be rerouted to other active radios.
- R_{high}: high load threshold for switching on radio. The parameter is used to determine if one or more radios would be activated as well as how many radios should be activated, which will be explained in the following sections.

B. Overview of green multi-radio FiWi access network

As FiWi access network is an integration of WMN and PON, the processes of transmitting traffic inside these two subnetworks are quite different due to the broadcast characteristic of WMN. When a demand of end-user arrives, the nearest wireless router will first compute a wireless multi-hop path and each wireless link on the path should allocate the required bandwidth for this demand. Then, the wireless router can transmit the data packets of the demand to its destination ONU through the path between them. During this process, the reasonable channel and bandwidth allocation scheme should be designed to reduce packet delay as well as interference. Thereafter, the destination ONU will send these packets to OLT in the specified transmission windows along the fiber link between them. In our design of green multi-radio FiWi access network, the ONU-sleep mechanism and radio-off mechanism are needed to schedule the power states of ONUs and radios, respectively. For the scheduling of ONU and radio states, a pair of thresholds is set respectively to determine the minimum load below which the network device (ONU or radio) can be switched into sleep/off state and the maximum load above which at least one sleep ONU or some related radios should be activated. In the scenario of high traffic load when no wireless path is available for the new arrived demand, there should be a strategy to optionally switch on some radios to maintain better QoS for end-users. In summary, the design of green FiWi access network is implemented by controlling the power states of network devices effectively at the same time maintaining better network performance.

C. Problem formulation of traffic routing

For the sake of better modeling the green FiWi access network design, the traditional shortest path routing model is presented mathematically at first, which is defined as a function $Shortest\_path(n^s_k, n^d_k, b_k, G), \forall k$. Then, the mathematical model can be defined as follows:

- **minimize:**

$$\sum\nolimits_{i=1}^{N} \sum\nolimits_{j=1}^{N} \xi^k_{(i,j)}. \tag{1}$$

- subject to:

$$\begin{aligned}&\textstyle\sum_{j=1}^{N}\left(e_{(i,j)}\cdot\xi_{(i,j)}^{k}\cdot b_k\right)-\sum_{j=1}^{N}\left(e_{(j,i)}\cdot\xi_{(j,i)}^{k}\cdot b_k\right)\\&=\begin{cases}b_k, & \forall v_i=n_k^s, i\in\{1,2,\cdots,N\},\\-b_k, & \forall v_i=n_k^d, i\in\{1,2,\cdots,N\},\\0, & \text{otherwise},\end{cases}\end{aligned}\tag{2}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{N}\xi_{(i,j)}^{k}\leq H,\tag{3}$$

$$\xi_{(i,j)}^{k}\cdot b_k\leq c_{(i,j)}^{r},\ \forall i,j\in\{1,2,\cdots,N\},\ i\neq j,\tag{4}$$

The objective in (1) is to find the shortest path by means of minimizing the number of hops. The constraint in (2) states that for all nodes of the network, the outgoing traffic should be equal to incoming traffic except for the source and the destination nodes. Equation (3) implies the path length constraint of each demand k, which limits the path length no longer than H hops. Equation (4) states that the residual capacity of each link along the routing path of demand k should be higher than the bandwidth requirement of demand k. Initially, $c_{(i,j)}^{r}=C_{(i,j)}$. Based on the model above, if the routing path of demand k exists, the function $Shortest\_path(n_k^s,n_k^d,b_k,G)$ will return 1, and 0 otherwise.

D. Problem formulation of green FiWi access network

With the purpose of saving as much as energy, network devices are equipped with different power levels. For the energy-saving of PON, each ONU is equipped with two power states, i.e., active and sleep. Active ONUs can transmit packets normally to OLT and wireless gateways. However, when an ONU goes into sleep state, its OLT-side transmitter and wireless gateway-side transmitter/receiver will be shut down. Thus, sleep state is a low-power state. To schedule the power states of ONUs and ensure the QoS provisioning ability of network, a pair of thresholds W_{high} and W_{low} are employed for each ONU to estimate its low and high load profile. The power state of each ONU can be determined by comparing its current load with W_{high} and W_{low}. Fewer active ONUs will lead to more energy to be saved. For the energy-saving of WMN, each radio is configured with the functionality of on/off state switching. Here, "off" represents such a power state of radio that no packet is received or transmitted, and just some necessary modules are kept on for monitoring messages. Thus, the off state consumes less energy than the on state. Our objective is to minimize the number of switched-on ONUs and radios, thus more energy can be saved. Therefore, the problem of green FiWi access network is mathematically formulated as follows:

- minimize:

$$\sum_{u=1}^{N_O}\chi_u^O+\sum_{p=1}^{N_W}\sum_{r=1}^{N_R}\chi_{(p,r)}^{W}.\tag{5}$$

- subject to:

$$Shortest\_path(n_k^s,n_k^d,b_k,G^{'})=1,\ \forall k\in\{1,2,\cdots,K\},\tag{6}$$

$$\begin{aligned}&wr_{(q,s)}\in Negb(wr_{(p,r)}),\ \text{if}\ e_{(p,q)}^{'}=1\ \text{or}\ q=p,\\&\forall p,q\in\{1,2,\cdots,N_W\},\ r,s\in\{1,2,\cdots,N_R\},\end{aligned}\tag{7}$$

The objective in (5) is to minimize the number of active ONUs and wireless radio interfaces. Equation (6) captures the fact that each traffic demand should be able to find an available routing path to transmit its packets. Equation (7) presents the neighbor domain of $wr_{(p,r)}$. Radio $wr_{(q,s)}$ is included in the neighbor domain of $wr_{(p,r)}$, if there exists a link between the wireless nodes (router or gateway) w_p and w_q or $q=p$. Here, $q=p$ elaborates that $wr_{(p,r)}$ and $wr_{(q,s)}$ are located in the same wireless node. We further introduce the constraints of ONU state switching as follows:

$$1\leq\sum_{u=1}^{N_O}\chi_u^O\leq N_O,\tag{8}$$

$$\chi_u^O=\begin{cases}0,\text{if}\ \eta_u^O<W_{low}\ \text{and}\ \eta_z^O<W_{high},\\\quad z\neq u,\text{and}\ \forall u,z\in\{1,2,\cdots,N_O\}\\\quad\sum_{z:\,\chi_z^O=1}\left(C_z^O-\eta_z^O\right)\geq\eta_u^O,\\1,\text{if}\ \eta_z^O\geq W_{high},\exists z\in\{1,2,\cdots,N_O\}\\\quad\text{and}\arg\{\max active\_radio\_num(o_l)\}=o_u,\\\quad\forall p,q\in\{1,2,\cdots,N_W\},l\in\{1,2,\cdots,N_O\},\end{cases}\tag{9}$$

The constraint in (8) guarantees that at least one ONU in the network should be active to carry the subsequent traffic demands. In (9), any ONU o_u can be switched into sleep state only if 1) load of o_u is lower than the low threshold W_{low}, 2) load of any other active ONU in the network is lower than the high threshold W_{high}, which guarantees that no ONU is high-loaded such that the network will not face the risk of traffic congestion after putting o_u into sleep state, and 3) total residual capacity of other active ONUs is higher than the load of o_u such that those active ONUs can carry the load of o_u with enough capacity. However, if there is an ONU o_z whose load is higher than W_{high} and at least one other ONU is in sleep state in the network, we should activate o_u whose neighbor on-state radio number is the maximum among all the sleep ONUs so as to prevent the network from congestion and maintain better QoS for end-users. Neighbor on-state radio number of ONU o_l is defined as in (10) which states the total number of on-state radios on the directly connected wireless gateways and two-hop connected wireless routers from o_l.

$$\begin{aligned}&active\_radio\_num(o_l)=\sum_{p:e_{(o_l,p)}=1}\sum_{r=1}^{N_W}\chi_{(p,r)}^{W}+\\&\sum_{q:e_{(o_l,p)}=1\text{and}e_{(p,q)}=1}\sum_{r=1}^{N_W}\chi_{(q,r)}^{W},l\in\{1,2,\cdots,N_O\},\end{aligned}\tag{10}$$

$$0\leq\sum_{r=1}^{N_R}\chi_{(p,r)}^{W}\leq N_R,\ \forall p\in\{1,2\cdots,N_W\},\tag{11}$$

$$\chi^W_{(p,r)} = \begin{cases} 0, \text{ if } \ \eta^W_{(p,r)} \leq R_{low} \text{ and} \\ \quad Shortest\_path(n^s_k, n^d_k, b_k, G^{'}) = 1, \\ \quad \forall \text{demand } k \text{ in } wr_{(p,r)}, \\ 1, \text{ if } R_{high} \leq \eta^W_{(q,s)} < R_{high} + (1 - R_{high})/2, \\ \quad \exists wr_{(q,s)} \in Negb(wr_{(p,r)}), \\ 1, \text{ if } \eta^W_{(q,s)} \geq R_{high} + (1 - R_{high})/2, \\ \quad \exists wr_{(q,s)} \in Negb(wr_{(g,h)}), \\ \quad \forall wr_{(g,h)} \in Negb(wr_{(p,r)}), \end{cases} \tag{12}$$

Equations (11) and (12) elaborate the constraints of radio state switching. The constraint in (11) guarantees that the number of active radios on each wireless router should be no larger than N_R. Equation (12) specifies the constraints for switching the power states of radios. On one hand, if any radio $wr_{(p,r)}$ whose current load is lower than the low threshold R_{low} and all the traffic demands in $wr_{(p,r)}$ can find rerouting paths on other active devices, then $wr_{(p,r)}$ should be switched off to save energy consumption of WMN. On the other hand, any wireless radio interface should be switched on if there exists another wireless radio in its first level of neighbor domain, whose current load is between the high threshold R_{high} and lower than $R_{high} + (1 - R_{high})/2$, such that the new switched on radio can carry the load of the original high-loaded radio to maintain better QoS. However, when the load is higher than $R_{high}+(1-R_{high})/2$, which means that the radio is extremely high-loaded, more radios should be switched on to afford the traffic load. Therefore, all the radios in the neighbor domain of all the wireless radios in the first level of neighbor domain of the extremely high-loaded radio, which is called the second level of neighbor domain, should be turned on. The two kinds of neighbor domain levels would be introduced in the following section. We update the residual network as follows:

$$\begin{aligned} V^{'} = V - \{o_u,\ wr_{(p,r)}\}, \text{ if } \chi^O_u = 0 \text{ and } \chi^W_{(p,r)} = 0, \\ \forall o_u \in V_O,\ w_p \in V_W, \end{aligned} \tag{13}$$

$$e^{'}_{(i,j)} = \begin{cases} 0, & \text{if } \chi^O_i = 0 \ \text{ or } \chi^O_j = 0 \ \text{ or} \\ & (\chi^W_{(i,r)} = 0 \ \text{ and } \gamma_{(i,j)} = r) \ \text{ or} \\ & (\chi^W_{(j,r)} = 0 \ \text{ and } \gamma_{(i,j)} = r), \\ & \forall v_i \in \{V_O \cup V_W\},\ r \in \{1, 2, \cdots, N_R\}, \\ e_{(i,j)}, & \text{otherwise}, \end{cases} \tag{14}$$

Specifically, equation (13) is defined to update the set of nodes, where the set of residual nodes includes all the network devices that are in active state. The set of residual links is updated by removing the invalid link caused by the sleep ONUs and off radios, as shown in (14).

Due to the traffic dynamics, the mathematical method such as Integer Linear Programming (ILP) is usually not feasible for the optimization problem of power states scheduling. Moreover, the mathematical formulation of some related constraints turns out to be nonlinear. Therefore, the sophisticated heuristics should be designed to solve it in reasonable time.

IV. HEURISTIC SOLUTIONS

Since a unified approach is not only hard to resolve the energy-saving problem in large scale FiWi access network but also not applicable at the dynamic traffic demands which are born with high randomness, in this section, we propose two heuristic algorithms called EAS for the scheduling of ONU power states and ERO for the scheduling of radio power states, respectively. Besides, a feedback mechanism is designed where the states of neighbor radios will be taken into account when it comes to activating an ONU.

A. Heuristic for scheduling of ONU power states

According to the proposed EAS, OLT is responsible for centrally scheduling the power states of all ONUs. To maintain the QoS for users, two thresholds W_{low} and W_{high} are introduced to estimate the traffic load of each ONU. In each polling cycle of EAS, each active ONU needs to detect its current load and send a report packet with its load information to OLT. Since OLT has received all the report packets, it will judge the power states of all ONUs by comparing their loads with the predefined thresholds and notify the ONUs about the power states information. When an ONU is switched into sleep state, its traffic would be rerouted to other active ONUs using *Dijkstra* algorithm. The procedure of the EAS algorithm is described in Algorithm 1.

Algorithm 1 EAS for scheduling of ONU power states

```
Input: $G(V, E), N_O, N_W, N_R, C_{(o_u,olt)}, W_{low}, W_{high}, u \in \{1, 2, \cdots, N_O\}, \ p, q \in \{1, 2, \cdots, N_W\}$.
Output: $\chi^O_u, u \in \{1, 2 \cdots, N_O\}$.
Each ONU sends a report packet with its load information to OLT;
Initialize $\chi^O_u \leftarrow 1, u \in \{1, 2 \cdots, N_O\}, u \leftarrow 1$;
while $u \leq N_O$ do
    if $\eta^O_u < W_{low}$ and $\eta^O_z < W_{high}, z \neq u$ and $\sum_{z:z\in\{1,2,\ldots,N_O\},\ \chi^O_z=1} (C_{(o_z,olt)} - \eta^O_z) \geq \eta^O_u$ then
        $\chi^O_u \leftarrow 0$;
        Reroute the traffic of $o_u$ to other active ONUs using Dijkstra;
    else
        if $\eta^O_u \geq W_{high}$ and $\exists z \in \{1, 2, \cdots, N_O\}, \chi^O_z = 0$ and $\forall p, q \in \{1, 2, \cdots, N_W\}, l \in \{1, 2, \cdots, N_O\}$, $\arg\{\max active\_radio\_num(o_l)\} = o_z$, then
            $\chi^O_z \leftarrow 1$;
        end if
    end if
    $u \leftarrow u + 1$;
end while
```

For the packet scheduling in EAS, we define four kinds of control packets REPORT, SLEEP, ACTIVE, and ALERT on the basis of traditional control packets in PON such as HELLO packet. As shown in Fig. 2, an OLT is connected with four ONUs through splitter. At the beginning, all ONUs are active and report their current loads to OLT through sending REPORT packets. When OLT receives all REPORT packets from ONUs, the EAS algorithm will be executed to decide

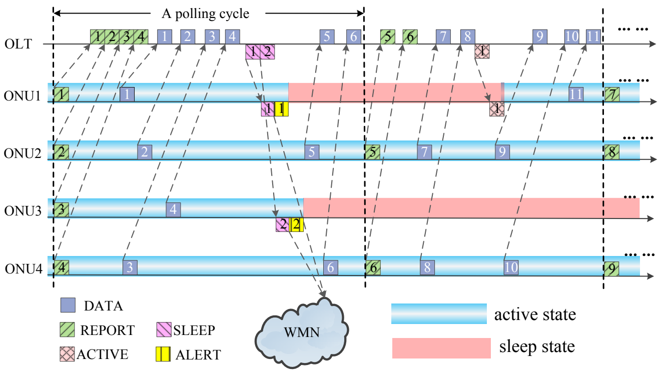


Fig. 2. Example of EAS scheduling.

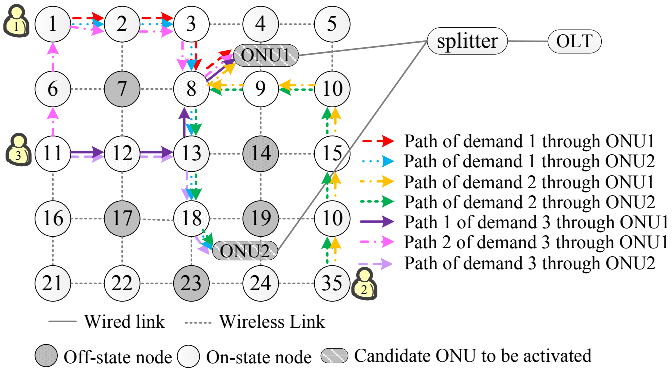


Fig. 3. Example of activating ONU.

which ONUs should switch into sleep states, e.g., ONU 1 and ONU 3. Accordingly, OLT sends a SLEEP packet to ONU 1 and ONU 3, respectively. When ONU 1 (or ONU 3) receives the SLEEP packet, it will first send an ALERT packet to each of its source wireless router through the wireless paths between them. The ALERT packet is used to notify the source wireless routers that their traffic should be rerouted as well as which packets should be rerouted. After sending ALERT packet, ONU 1 (or ONU 3) will go into sleep state. In the next polling cycle of EAS, the active ONUs will continue sending REPORT packets to OLT, while the sleep ONUs do nothing because their OLT-side transmitters have been switched off. When the traffic load of any active ONU increases to higher than W_{high}, OLT will activate at least one sleep ONU, e.g., ONU 1, by sending an ACTIVE packet to it. Then, ONU 1 will go into active state and carry the subsequent traffic.

When it comes to selecting an appropriate ONU to relieve the pressure of the high-loaded OUN, a feedback mechanism is proposed where the ONU with maximum on-state neighbor radio number is chosen. For example in Fig. 3 where each wireless node is equipped with only one radio, assuming there are two candidate sleep ONUs (i.e., ONU 1 and ONU 2) and three traffic demands from the nodes 1, 35, and 11 respectively are arriving currently. It can be observed that the on-state radio number of ONU 1 and ONU 2 are 4 (i.e., node 3, 8, 9, and 13) and 2 (i.e., node 13 and 18), respectively. For demand 1 and 2, it is easier to find shorter paths while activating ONU 1 than ONU 2. For demand 3, more feasible routing paths would be found while activating ONU 1. On the contrary, only one path is found if activating ONU 2, which means that the ONU with more on-state neighbor radios makes it easier for end users to not only find shorter path but also decrease the probability of traffic congestion. Thus, ONU 1 whose neighbor on-state radio number is higher will be chosen to activate in this case.

B. *Heuristic for scheduling of radio power states*

As mentioned in section III, a radio will have the probability to be switched off for energy saving when its load is lower than the low load threshold. The ERO algorithm which is loaded in OLT is proposed to periodically detect the low-loaded radios and reroute their traffic by using other switched-on radios. In each polling cycle of ERO, the stage of activating radios would be implemented firstly, and the sleeping stage would be executed subsequently.

In the activating stage, there are two levels of judgment and activating actions. At the first level when the load of a radio is between R_{high} and $R_{high} + (1 - R_{high})/2$, all the off-state radio in the first level of neighbor domain of the radio should be switched on. When the load of a radio is higher than $R_{high} + (1 - R_{high})/2$ which means that the radio is extremely high-loaded, then the off-state radios in the first and second levels of neighbor domain should be switched on to relieve the pressure of the radio. For example in Fig. 4, assuming the load of $wr_{(13,r)}$, $r \in \{1, 2, \cdots, N_R\}$ on node 13 is between R_{high} and $R_{high} + (1 - R_{high})/2$, the radios of nodes 8, 12, 14, and 18 and all the other radios on node 13 (not shown in Fig. 4), which compose the first level neighbor domain of $wr_{(13,r)}$, should be activated. Furthermore, while the load of $wr_{(13,r)}$ is higher than $R_{high} + (1 - R_{high})/2$, the radios of nodes 3, 7, 9, 11, 15, 17, 19, and 23, which compose the second level of $wr_{(13,r)}$, should be activated as well on the basis of the first level of its neighbor domain. The advantage of setting the two levels of neighbor domains and optionally activating the corresponding radios in the domains is to avoid traffic congestion according to current network load. Since the network devices in the local network surrounding the high-loaded radio is almost active after activating radios in the two levels of the target radio, network congestion can be avoided at the best effort. As shown in Fig. 4, by activating radios in the two levels of neighbor domains of the high-loaded radio on node 13, more optional traffic routing path could be chosen such that the probability of network congestion would be greatly reduced. For example, the original routing path for traffic demand of node 11 is $\langle 11 \rightarrow 12 \rightarrow 13 \rightarrow 8 \rightarrow \text{ONU1} \rightarrow \text{splitter} \rightarrow \text{OLT}\rangle$. There are two candidate routing paths, i.e., $\langle 11 \rightarrow 12 \rightarrow 17 \rightarrow 18 \rightarrow \text{ONU2} \rightarrow \text{splitter} \rightarrow \text{OLT}\rangle$ and $\langle 11 \rightarrow 12 \rightarrow 7 \rightarrow 8 \rightarrow \text{ONU1} \rightarrow \text{splitter} \rightarrow \text{OLT}\rangle$ for traffic demand from node 11 in case the original routing path becomes invalid due to high-loaded. It is obvious that the radios on the same wireless node have completely the same first and second levels of neighbor domains.

In the sleeping stage, all the other radios that are not mentioned in the activating stage will be sorted and put into a specified queue in the order of increasing traffic load. The lower-loaded radios will be earlier put into the queue and

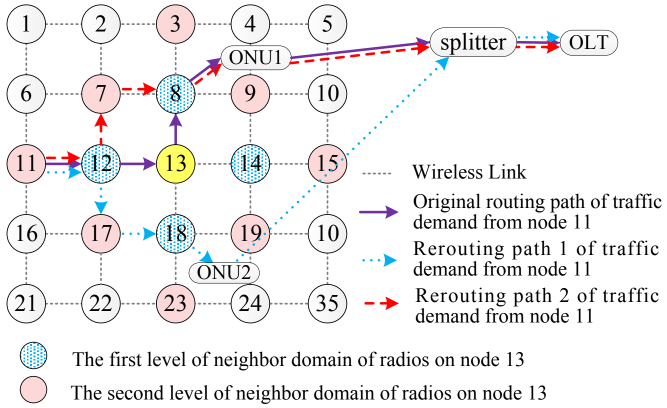


Fig. 4. The two levels of neighbor domain of wireless radios.

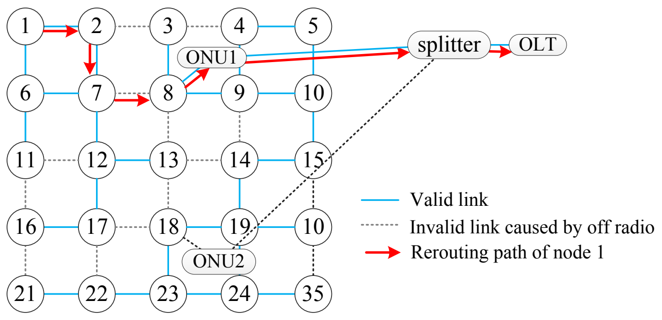


Fig. 5. Turning on radio when there is no path for new arrived demand.

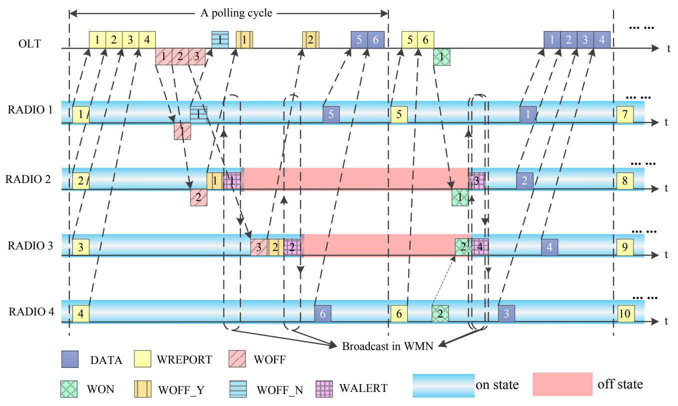


Fig. 6. Example of ERO scheduling.

extracted earlier as well because lower-loaded radios can be more easily switched off. Then, for each radio in the order of increasing load, the *Dijkstra* algorithm which is executed by the processor module of wireless router will be used by the corresponding router to reroute the traffic of the radio that is to be switched off into other switched-on radios. For each radio $wr_{(p,r)}$, we need to find an alternative path for each traffic flow whose transmission links are broken when the radio is switched off. If all the rerouting paths of these traffic demands in $wr_{(p,r)}$ could be found, the radio will then be switched off to save energy. Meanwhile, for each influenced demand, an WREROUTE packet will be sent to the source wireless router to inform it to reroute the rest packets of the demand on the previously computed routing path. However, nothing would be done if at least one demand cannot find the alternative path.

Besides, in case that there are too many radios switched off and the residual capacity of wireless front-end cannot carry the new arrived traffic load, the *Dijkstra* algorithm will be executed on the potential network topology, and the non-active wireless radios of the potential routing path will be switched on so as to carry new traffic demand with the guaranteed QoS as well as avoiding traffic congestion. The potential network topology is defined as the topology assuming that all the wireless radios are in on state according to the residual capacity of current network topology. For example in Fig. 5, while node 1 finds no path for its traffic flow, it will execute the *Dijkstra* algorithm on the potential network topology which includes the invalid links caused by sleeping devices in WMN and the current network topology. It should be noticed that the invalid links in PON would not be included in the potential network topology. Since node 1 finds the feasible path that covers the invalid links, the wireless radio related with the invalid link would be turned on, that is, $\gamma_{(7,8)}$ and $\gamma_{(8,7)}$, if they are in the off state. The procedure of ERO is described in Algorithm 2.

The diagram of ERO is shown in Fig. 6 where OLT plays the role of decision maker of radio states and several kinds of control packets are introduced to achieve the message exchanging between OLT and wireless radios. As shown in Fig. 6, take four wireless radios (designated by RADIO 1, RADIO 2, RADIO 3, and RADIO 4) for example, when a new ERO cycle comes, all the on-state wireless radios will report their traffic loads using WREPORT packets, according to which OLT will determine the state of each wireless radio, and transmit WON or WOFF packets to them to identify their oncoming power states. If a radio has received a WOFF packet, it will first check if all of its current traffic flows can be transmitted to other on-state radios, and the WOFF_Y or WOFF_N packet will be returned to OLT to inform the radios that have been (RADIO 2 and RADIO 3) or not been (RADIO 1) switched into off state, respectively. While a wireless radio receives the WON packet, it will turn on its transmitter to carry the traffic load (RADIO 2). Moreover, while there arrives a new traffic demand that requires an off-state radio to turn on and transmit its data packets, the W_ON packet can also be used to transmit on-state command among radios (i.e., from RADIO 4 to RADIO 3). In addition, while a radio changes its power state, a WALERT packet will be broadcasted to the whole WMN to inform other wireless radios about its residual bandwidth capacity (0 while in off state).

C. EE (EAS & ERO) scheme

The EE scheme is implemented by combining the EAS and ERO algorithms strategically. As shown in Fig. 7, after the initialization of network topology and traffic demand model, the whole network will go into an "idle" state waiting for triggers of events. There are mainly four kinds of triggers for "idle" state as follows:

- When a new demand of end-user arrives, *Dijkstra* will be used to compute the routing path from source wireless

Algorithm 2 ERO for scheduling of radio power states

```
Input: $G(V,E), N_W, N_R, R_{low}, R_{high}$
Output: $\chi^W_{(p,r)}, p \in \{1,2,\cdots,N_W\}, r \in \{1,2,\cdots,N_R\}$.
Turning on radios - case for high-loaded radios:
Initialize $\chi^W_{(p,r)} \leftarrow 1, p \in \{1,2,\cdots,N_W\}$, $r \in \{1,2,\cdots,N_R\}, p \leftarrow 1, r \leftarrow 1, n \leftarrow 1, num \leftarrow N_W \cdot N_R$, put all the radios in queue $Q$;
while $p \leq N_W$ do
    while $r \leq N_W$ do
        if $R_{high} \leq \eta^W_{(p,r)} < R_{high} + (1 - R_{high})/2$ then
            $\chi^W_{(q,s)} \leftarrow 1, \forall wr_{(q,s)} \in Negb(wr_{(p,r)})$;
            Extract $wr_{(q,s)}$ from $Q$;
            $num \leftarrow num - 1$;
            $r \leftarrow r + 1, n \leftarrow n + 1$;
        else if $\eta^W_{(q,s)} \geq R_{high} + (1 - R_{high})/2$ then
            $\chi^W_{(q,s)} \leftarrow 1, \forall wr_{(q,s)} \in Negb(Negb(wr_{(p,r)}))$;
            Extract $wr_{(q,s)}$ from $Q$;
            $num \leftarrow num - 1$;
            $r \leftarrow r + 1, n \leftarrow n + 1$;
        end if
    end while
    $p \leftarrow p + 1$;
end while
Turning off radios:
Rank all radios in $Q$ in an increasing order of their loads;
while $n \leq num$ do
    Get the radio $wr_{(q,s)}$ with the least load among all radios in queue $Q$;
    if $\eta^W_{(q,s)} \leq R_{low}$ then
        For each demand on radio $wr_{(q,s)}$, compute the alternative path by using Dijkstra for traffic rerouting;
        if all demands on $wr_{(q,s)}$ have the alternative paths then
            Reroute the traffic of $wr_{(q,s)}$ on the rerouting path;
            Switch off the radio $wr_{(q,s)}$: $\chi^W_{(q,s)} \leftarrow 0$;
            Extract $wr_{(q,s)}$ from $Q$;
        end if
    end if
    $n \leftarrow n + 1$;
end while
Turning on radios - case for no feasible path:
When a new demand $k$ arrives, implement the following steps:
Use Dijkstra to compute the routing path for demand $k$;
if the path is available then
    Transfer the packets of demand $k$;
else
    Compute the routing path on the potential network topology for demand $k$ again;
    if the path is available then
        Turn on the off state radio used by the available path;
        Transfer the packets of demand $k$;
    else
        Put the demand $k$ into the sending buffer;
    end if
end if
```

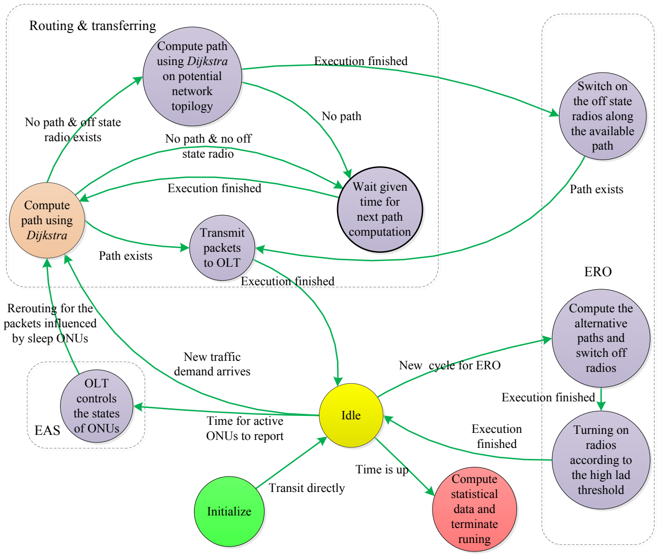


Fig. 7. Illustration of states transition in the EE scheme.

router to OLT. If no path is available and there exist some radios that are in the off state, the *Dijkstra* will be used again to compute the potential path on the potential network topology. Then, if there exists a feasible path on the potential network topology, all the switched-off radios along the feasible path will be turned on to carry the traffic. However, if there is not any switched-off radio or the potential path is not found, the demand will be buffered and wait for the next routing computation after some time, which happens rarely because traffic congestion should be considered in network deployment. Once the routing path is determined, the data packets of the demand can be transmitted to OLT.

- When a new EAS polling cycle starts, EAS will be executed to determine the power states of all ONUs through the interaction of control packets (e.g., REPORT, SLEEP and ACTIVE) between ONUs and OLT.
- When a new ERO polling cycle starts, the operation of turning on radios according to the high load threshold will be carried out first and the operation of rerouting traffic and switching off radios will be executed subsequently to reduce the energy consumption of WMN.
- When the running time of network terminates, the statistical data will be computed for network performance evaluation.

V. PERFORMANCE EVALUATIONS

A. Simulation settings

The professional OPNET modeler 14.5 is employed as simulation platform to verify the effectiveness of the proposed scheme. As shown in Fig. 8, the simulated network topology contains one OLT, 4 ONUs (designated by ONU_i, $i = 1,2,3,4$), 2 wireless gateways for each ONU (designated by WG_i, $i = 1,2,3\cdots,8$) and 41 wireless routers (designated by WR_i, $i = 1,2,3\cdots,41$). The distance between OLT and ONUs is set to 1km. The WMN is deployed according to

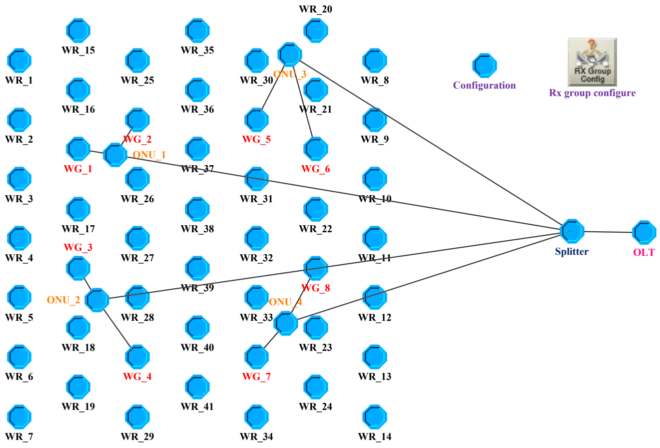


Fig. 8. Simulated network topology.

TABLE II

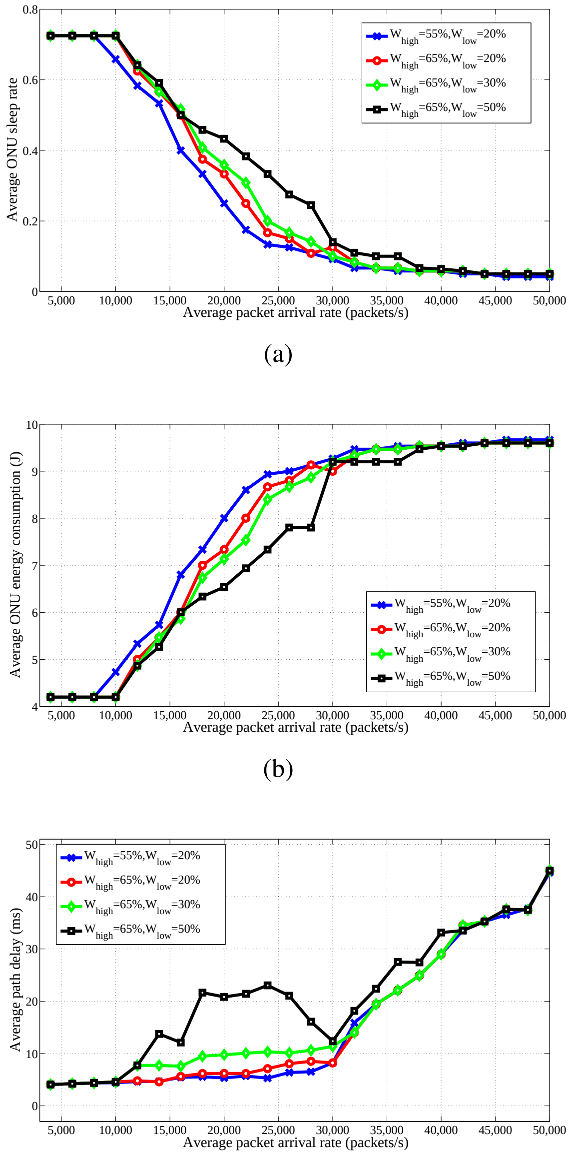
SETTINGS OF LINK CAPACITY, AWAKE TIME, AND POWER LEVELS

parameter	network device	value
link capacity	feeder fiber link cable link wireless link	1Gbps 54Mbps 54Mbps
awake time	ONU radio	3.5ms 5ms
power of active/on state	ONU radio	10W 3.762W
power of sleep/off state	ONU radio	2W 0.957W

the mesh topology. The distance between adjacent wireless routers is set to 60m, which indicates that the size of simulated area is 500m×500m. Each wireless router is configured with two radios. Each radio has a transmission radius of 100m [18]. Different wireless links of the same channel share its capacity by means of time division multiplexing. The radios are allocated channels according to IEEE 802.11a, with 11 orthogonal channels of 20MHz bandwidth for outdoor communication, starting at 5.5GHz [18], [19]. The settings of link capacity, awake time of each network device and power levels are shown in Table II [13], [15], [17], [20]. It should be noticed that the power consumed for awaking an ONU or a wireless radio is same as the power of active/on state of the corresponding devices [15]. The probability of traffic demands existing on each wireless router is 0.5 and the distribution of traffic load will be updated periodically. For each wireless router with traffic demands, the arrival of demands follows Poisson distribution with the packet size of 512 bytes.

B. Simulation results and analysis

In this subsection, we first evaluate the impact of the parameters in EE, such as the high threshold W_{high} and low threshold W_{low} of ONU, and the high threshold R_{high} and low threshold R_{low} of radio on the network performance in terms of average ONU/radio sleep/off rate, average ONU/radio energy consumption and average path delay. Then, we will analyze the performance advantage of the EE scheme by comparing it with the network scenarios in which no energy-saving technique is considered and the QoS-aware Energy-saving (QE) algorithm [15] is used, respectively. Here, the QE algorithm implements the fast sleep state on network devices.



(a)

(b)

(c)

Fig. 9. Impact of ONU load thresholds W_{high} and W_{low} on network performance.

1) Impact of the EE parameters on network performance: Figure 9 shows the impact of W_{high} and W_{low} on average ONU sleep rate, average energy consumption of each ONU and average path delay. With the increase of average packet arrival rate, average ONU sleep rate falls down with less energy to be saved, meanwhile, the average path delay increases. Specifically, average path delay goes extremely high while network load is higher than 35,000 packets/s which means the network congestion happens.

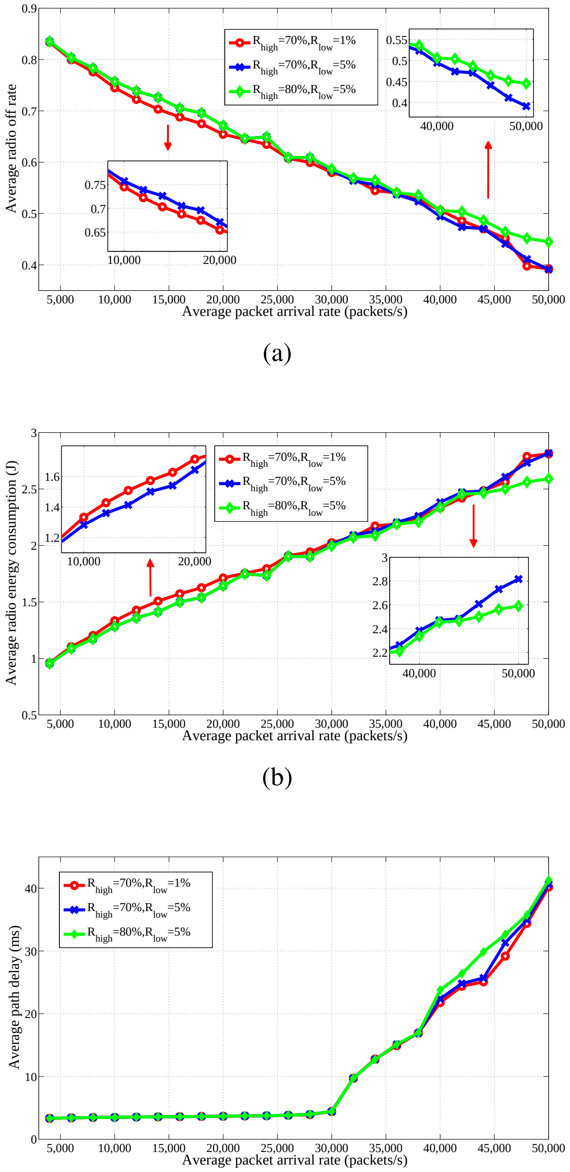
According to the proposed EE scheme, at least one sleep ONU should be waked up when any active ONU has the traffic load higher than W_{high}. Thus, in the case of higher W_{high}, there will be less opportunity for sleep ONUs to be waked up, which indicates higher ONU sleep rate as shown in Fig. 9(a). Therefore, comparing the two lines with circular marker and cross marker in Fig. 9(b), we can observe that more energy will be saved by setting higher W_{high}. On the other hand, W_{low} is set for OLT to determine whether an ONU should be switched into sleep state. An ONU can be switched into sleep state only if it has the traffic load lower than W_{low}. Therefore, higher W_{low} will lead to larger ONU sleep rate as shown in the three lines with circular, diamond and square markers in Fig. 9(a) meanwhile more energy will be saved which can be seen in Fig. 9(b).

Meanwhile, the cost of energy-saving is the large path delay shown in Fig. 9(c). As higher W_{high} and W_{low} contribute to more ONU sleep rate as mentioned above, the average path delay will also rise. Specifically, average path delay of the line with square marker displays a fierce jitter while network load is low, which can be explained as follows. Since higher W_{low} causes more ONUs being switched off and these sleep ONUs cannot be activated while the load of the only active ONU is lower than W_{high}, all the traffic will be routed on the only active ONU, which leads to the rising queuing delay. Thus, the average path delay goes higher. With the network load increasing, other sleep ONUs will be activated and network demand will be assigned equally on the active ONUs and the average path delay decreases due to lower queuing delay of ONUs. In conclusion, W_{high} and W_{low} should be set up appropriately so as to balance the tradeoff between energy consumption and QoS, and the ONU sleep rate should be controlled not too high by adjusting W_{high} and W_{low} to reduce the path delay caused by queuing delay.

Figure 10 shows the impact of high threshold R_{high} and low threshold R_{low} on average radio off rate, average energy consumption of each radio and average path delay. With the increase of average packet arrival rate, average radio off rate will drop down with less energy to be saved, meanwhile the average path delay increases.

Comparing the two lines with diamond and cross markers, R_{high} has more influence on network performance while network load is high. Higher R_{high} brings about higher average radio off rate, more saved energy and higher average path delay. Comparing the two lines with circular and cross markers, R_{low} has more influence on network performance while network load is low. Higher R_{low} will lead to higher average radio off rate, more energy to be saved and higher average path delay. However, while changing R_{high} and R_{low}, the change of average path delay is unobvious owing to the high flexibility of WMN.

2) Comparative analysis of the EE scheme: In this part, we put more emphasis on the comparative analysis of the EE scheme with the QE scheme proposed in [15] and use the network performance without energy-saving technique as the lower bound. In QE, every network device (ONU and wireless radio) has two levels of power states, active and sleep, which can be determined according to current network load and the predicted path delay. In sleep state, each device is in fast sleep state as described in section II. And the cycle of being in active or deep sleep state depends on the the predicted path delay and the pre-set path delay threshold for the reason that smaller cycle will bring about lower path delay which is caused by lower queuing delay. However, smaller state-switching cycle will lead to more ONU or radio arousal times which can increase the network energy consumption. It should be noted that the maximum ONU sleep rate and radio off rate of the QE scheme will be no higher than 50% which happens when all the devices are in sleep/off state.



(a)

(b)

(c)

Fig. 10. Impact of radio load thresholds R_{high} and R_{low} on network performance.

As shown in Fig. 11, both average ONU sleep rate and radio off rate of EE and QE fall down with the increase of average packet arrival rate. These lead to the increase in energy

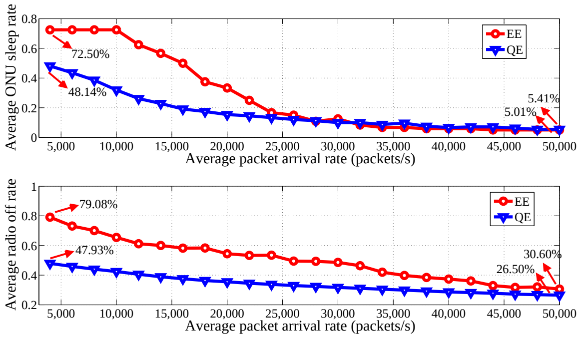


Fig. 11. Average ONU sleep rate and radio off rate.

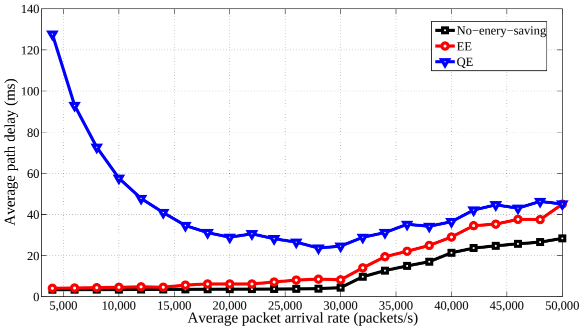


Fig. 13. Comparison of average path delay.

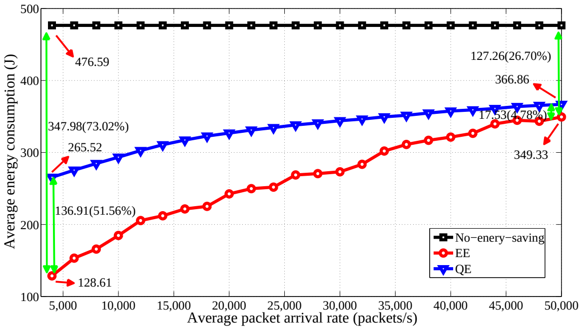


Fig. 12. Comparison of average energy consumption.

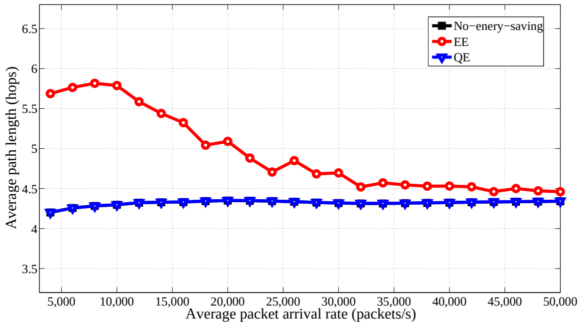


Fig. 14. Comparison of average path length.

consumption of ONUs and radios such that the average energy consumption of the network increases as shown in Fig. 12, where “No-energy-saving” denotes the network scenario without any energy-saving consideration. Specifically, the “No-energy-saving” scenario keeps constant energy consumption as no device is switched into low-power state.

Through the analysis of Fig. 11 and Fig. 12 together, we can conclude some tips as follows.

- Energy consumption of No-energy-saving is the highest (i.e., 476.59J/s) among the three scenarios, and the energy consumption is independent of network load. In the QE scheme, while the average packet arrival rate changes from 5,000 to 50,000 packets/s, the energy consumption increases from 265.52J/s to 366.86J/s as the sleep rate of network devices decreases. Specifically, the average ONU sleep rate decreases from 48.14% to 5.41% and the average radio off rate decreases from 47.93% to 26.50%.
- In the EE scheme, the average sleep/off rate of network devices (ONU and radio) falls down along with the increasing network load. Specifically, as shown in Fig. 11, the highest average ONU sleep rate and radio off rate are 72.50% and 79.08%, respectively, while the network resource is enough such that there is no traffic congestion and less queuing delay, which is obviously higher than the 48.14% and 47.93% in QE. The lowest average ONU sleep rate and radio off rate are 5,41% and 30.60%. It could be seen that, in EE, there is not a limit on the maximum 50% network devices sleep/off rate as in QE. Moreover, when the network is high-loaded, the ONU sleep rate should be controlled not too high in order to maintain better QoS.
- As aspect of average energy consumption in Fig. 12, the average energy consumption changes from 128.61J/s to 349.33J/s when the average packet arrival rate changes from 5,000 to 100,000 packets/s. Compared with No-energy-saving scenario, the maximum energy saved is 347.98J/s which accounts for 73.02% of total energy consumption and when the average packet rate is high, the minimum energy saved is 127.26 J/s accounting for 26.70% of total energy consumption of No-energy-saving scenario. In comparison with the QE scheme, the maximum and minimum energy saved are 136.91J/s and 17.53J/s accounting for 51.56% and 4.78% of total energy consumption of QE, respectively.
- As for the monetary value of energy-saving in EE, take the average electricity price from January to November in America [21] which is \$36.33 per MWh for example, while the FiWi access network is deployed with 1 OLT, 4 ONUs and 49 wireless routers which covers a area of 500m×500m, we can save a maximum and minimum of 110.75 and 40.50, 43.57 and 5.58 dollars every year compared to No-energy-saving and QE scenarios, whose maximum energy cost are 151.67 and 116.75 dollars respectively. More important, the energy-saving FiWi access network scheme proposed in this paper makes contribution to promote the construction of green networks project and reduces the carbon footprint of the Information and Communication Technology (ICT).

To analyze the performance loss caused by energy-saving, Fig. 13 and Fig. 14 show the comparison of average path delay and average path length, respectively. In EE, the result is obtained by setting W_{high}=65%, $W_{low} = 20\%$, $R_{high} = 70\%$ and R_{low}=1%. It can be observed that the average path delay of QE and No-energy-saving scenarios are the same because of the same shortest-path algorithm without the consideration of network device state. Nevertheless, as shown in Fig. 14 the average path length of EE is a little higher than both QE and No-energy-saving scenarios and experiences a generally decreasing trend because more ONUs would keep active to carry higher traffic load. Larger number of active ONUs means it easier for a demand to find out the shorter path for traffic routing. We can observe from Fig. 11 that the average path delay grows up gradually when the average packet arrival rate increases from 5,000 to 50,000 packets/s in the No-energy-saving and EE scenarios. Moreover, the path delay will become higher under the situation that the EE scheme is employed in the network because of higher average path length described above. However, the average path delay is extremely high in QE because when network devices are in sleep state, the packets will be queued until the network devices are activated, which brings about large queuing delay. When network load goes higher, there is less network devices sleep rate shown in Fig. 9, thus the queuing delay decreases and the average path delay meets a slight decline. On the contrary, in EE, the rerouting mechanism which reroutes the current loads of sleep devices onto other active ONUs and radios guarantees that there is no packet in sleep devices waiting for being transmitted. Therefore, the average path delay is lower than the QE scenario.

In conclusion, the average path length of EE is slightly higher than No-energy-saving, but its average path delay is obviously lower than QE with more energy being saved, especially when the network is low-loaded. Therefore, the proposed EE scheme is effective in terms of both energy-saving and network performance.

VI. CONCLUSION

In this paper, we have proposed a novel scheme called EE, composed of two algorithms EAS and ERO, for the comprehensive energy-saving of multi-radio FiWi access network. In the EE scheme, EAS and ERO are responsible for the scheduling of power states of ONUs and wireless radios by judging the load profile of each network device, respectively. Meanwhile, the QoS provisioning ability of network is also well guaranteed by rerouting the traffic of each sleep device to other active devices. Simulation results have shown that the portion of energy saved by the EE scheme varies from 26.70% to 73.02% and from 4.78% to 51.56% in a wide range of traffic load compared to the No-energy-saving and QE scenarios, respectively. Therefore, the EE scheme is feasible and promising for the energy-saving design of multi-radio FiWi access network.

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