SCIENCE CHINA
Information Sciences

# A new integrated energy-saving scheme in green Fiber-Wireless (FiWi) access network

YeJun LIU, Lei GUO, LinCong ZHANG and JiangZi YANG

Citation: SCIENCE CHINA Information Sciences **57**, 062307 (2014); doi: 10.1007/s11432-013-4958-7

View online: https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

View Table of Contents: https://engine.scichina.com/publisher/scp/journal/SCIS/57/6

Published by the Science China Press

**Articles you may be interested in**

Optically injection-locked Fabry-Perot laser diodes based radio-over-fiber system for hybrid fiber-wireless access networks
SCIENCE CHINA Technological Sciences **56**, 608 (2013);

Energy-saving PPM schemes for WSNs
Science in China Series F-Information Sciences **51**, 571 (2008);

Tempospacial energy-saving effect-based diagnosis in large coal-fired power units: Energy-saving benchmark state
SCIENCE CHINA Technological Sciences **58**, 2025 (2015);

Study of a Catalyst for Energy-Saving Natural Gas Steam Reforming
Journal of Natural Gas Chemistry **12**, 135 (2003);

A novel adaptive multiple-access scheme for wireless chip area network
SCIENTIA SINICA Informationis **46**, 100 (2016);

**SCIENCE CHINA**
Information Sciences

• RESEARCH PAPER •

June 2014, Vol. 57 062307:1–062307:15
doi: 10.1007/s11432-013-4958-7

# A new integrated energy-saving scheme in green Fiber-Wireless (FiWi) access network

LIU YeJun, GUO Lei*, ZHANG LinCong & YANG JiangZi

*College of Information Science and Engineering, Northeastern University, Shenyang* 110819*, China*

Received February 4, 2013; accepted April 23, 2013

**Abstract** Energy savings in Internet have been regarded as a significant technical issue for academic and industrial community. Particularly, access network accounts for more than 70% of the total energy consumption of Internet. As a promising access technique, Fiber-Wireless (FiWi) network not only enables the cost-effective broadband access, but also provides more opportunities for energy savings. Previous works mostly focused on the energy savings in the optical back-end of FiWi. Generally, they extended the Optical Network Unit (ONU) sleep mechanisms initially designed for Passive Optical Network (PON) to FiWi by combining with the wireless rerouting. However, most of these works left the energy savings in the wireless front-end untouched. In fact, when one or more ONUs in the network is/are sleeping, many wireless components remain idle or underutilized which cause a lot of energy waste. Motivated by this, we propose a new integrated Wireless-Optical Energy Savings (WOES) scheme for the comprehensive energy savings in FiWi. The WOES scheme consists of two interactive modules, Energy-Efficient ONU Management (EEOM) and Energy-Aware Topology Configuration (EATC). EEOM aims at the energy savings in the optical back-end by putting the low-load ONUs into sleep state. A pair of thresholds is introduced into EEOM to maintain the states of ONUs. As soon as ONUs states change, EATC will reconfigure the wireless topology by putting the idle Radio Interfaces (RIs) into standby state, thus minimizing the energy consumption of the wireless front-end. Simulation results show that the WOES scheme can reduce the energy consumption significantly with just a little performance degradation in network throughput and end-to-end delay.

**Keywords** Fiber-Wireless (FiWi) network, energy savings, ONU sleep, radio interface standby

**Citation** Liu Y J, Guo L, Zhang L C, et al. A new integrated energy-saving scheme in green Fiber-Wireless (FiWi) access network. Sci China Inf Sci, 2014, 57: 062307(15), doi: 10.1007/s11432-013-4958-7

## 1 Introduction

Energy-efficient Internet has been significantly gaining the academic and industrial attention in the past few years. The reasons may be attributed to not only the ecological issue of reducing greenhouse gas emissions but also the eager of service providers for lower energy expenditure [1,2]. As the "last mile" of Internet, access network is a major energy contributor to Internet because it comprises a large part of the network infrastructure and contains huge number of active components. It is estimated that the access network accounts for more than 70% of the total energy consumption of Internet [3]. Due to the explosive growth of bandwidth-intensive applications, it is foreseen that access network will suffer from

*Corresponding author (email: haveball@gmail.com)

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

© Science China Press and Springer-Verlag Berlin Heidelberg 2014

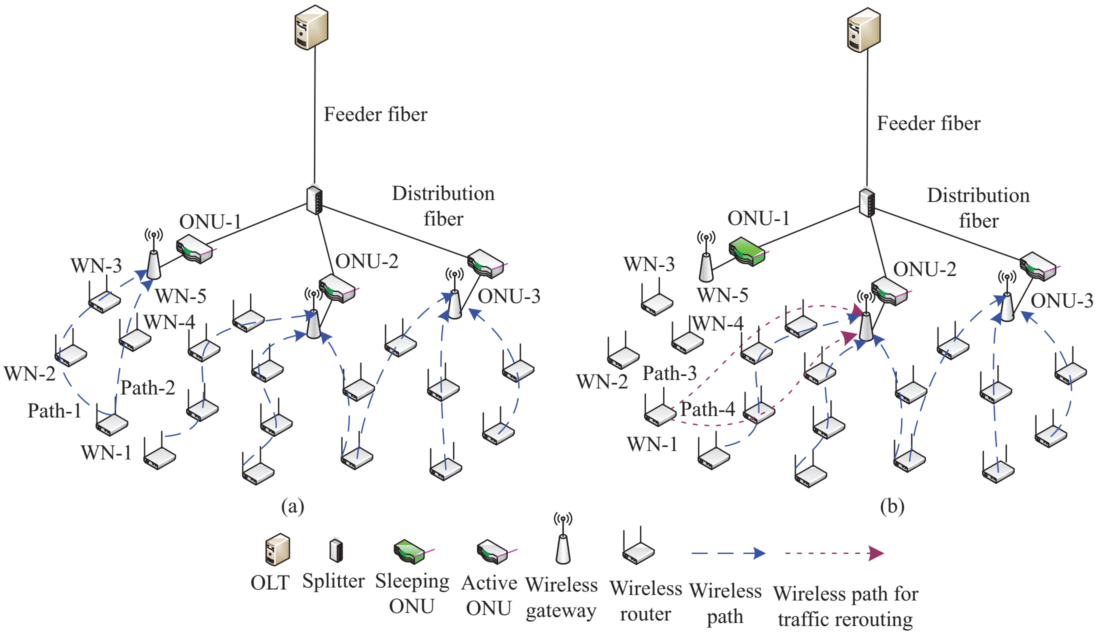


**Figure 1** (Color online) Architecture of FiWi access network.

a dramatic increase of energy consumption in the near future. Therefore, the energy savings in access network have been widely acknowledged as one of the enabling techniques for energy-efficient Internet.

As a promising access technique, Fiber-Wireless (FiWi) network aims to provide a cost-efficient broadband access solution by integrating the technical merits of wireless and optical access networks [4–7]. A typical FiWi architecture consists of a Wireless Mesh Network (WMN) at the front-end and a Passive Optical Network (PON) at the back-end [8,9]. The wireless gateway is connected to the Optical Network Unit (ONU) by wired cable as the interface between wireless front-end and optical back-end. For example, Figure 1 shows a FiWi network including three ONUs. This hybrid architecture not only enables the cost-efficient broadband access, but also provides more opportunity for energy savings. In the traditional PON, a common approach for energy savings is to put the low-load ONUs into sleep state [10–14]. During the ONU sleep period, the data packets will be queued at the ONU until the active period. Longer sleep period of the ONU means larger queuing delay of the data packets. Thus, the ONU sleep period is usually set to be short enough for the purpose of satisfactory end-to-end delay. This not only increases the technical complexity of the ONU sleep mechanism, but also suppresses the potential of energy savings in PON. However, in the FiWi network, each ONU to sleep can reroute its traffic to other active ONUs through the wireless paths between them. Thus, the ONUs in FiWi can enjoy longer sleep period which contributes to better energy savings. Therefore, FiWi has been considered as one of the promising architectures for the design of energy-efficient access network [15].

Some effort have been made to investigate the issue of energy savings in the FiWi network [15–18], most aiming to reduce the energy consumption of the optical back-end by extending the ONU sleep mechanisms in PON to FiWi and combining them with the wireless rerouting. However, the energy savings in the wireless front-end are left untouched. In fact, when one or more ONUs is/are sleeping, only a part of wireless components (e.g., radio interfaces) are used to route the traffic to the active ONUs while many other wireless components remain idle. The idle wireless components also need electricity provision which causes much energy waste. Therefore, there exists the opportunity for energy savings in wireless front-end if the idle wireless components are shut down or switched to standby state (i.e., low-power state). For example in Figure 1(a), there are three active ONUs ONU-1, ONU-2 and ONU-3 carrying 2, 3 and 3 connections, respectively. Each connection is allocated one wireless path and all Radio Interfaces (RIs) in the wireless path should be active for routing traffic. Particularly, the two connections sent to ONU-1 are allocated the wireless paths Path-1 and Path-2 respectively, where Path-1 goes through the wireless routers WN-1, WN-2, WN-3 and the wireless gateway WN-5, and Path-2 goes through the wireless routers WN-1, WN-4 and the wireless gateway WN-5. When ONU-1 is put into

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

sleep state as shown in Figure 1(b), the connections sent to ONU-1 will be rerouted to ONU-2 through the wireless paths Path-3 and Path-4. Accordingly, WN-2, WN-3, WN-4 and WN-5 become idle. If all RIs of WN-2, WN-3, WN-4 and WN-5 are put into standby state, the energy consumption will be further reduced.

Motivated by the above considerations, in this paper, we focus on the issue of integrating wireless and optical energy savings in FiWi which is less mentioned previously. An efficient scheme called Wireless-Optical Energy Savings (WOES) is proposed to combine ONU sleep mechanism with RI standby mechanism. Generally, WOES consists of two interactive modules, Energy-Efficient ONU Management (EEOM) and Energy-Aware Topology Configuration (EATC):

- The EEOM module is used for the energy savings in the optical back-end. We employ a pair of thresholds, i.e., Low Threshold (LT) and High Threshold (HT), to maintain the states of ONUs. The active ONUs, whose normalized traffic load (defined as the ratio of load to capacity) is less than or equal to LT, will be put into sleep state to reduce energy consumption. Accordingly, the affected traffic will be wirelessly rerouted into other active ONUs. When any active ONU has the normalized traffic load higher than or equal to HT, one or more sleeping ONUs will be activated in order to alleviate the traffic load of the active ONUs. Thus, each ONU has two alternative states, i.e., sleep or active. The states of all ONUs in the network constitute an ONU State Set (OSS).
- The EATC module is used for the energy savings in the wireless front-end. In EATC, we will dynamically reconfigure the wireless topology by putting the idle RIs into standby state. It is guaranteed that each wireless router in the network can connect to at least one active ONU with the constraint of wireless path length. We compute a RIs standby solution for each OSS with the objective of minimizing the energy consumption of wireless front-end. Once the OSS of the network changes, the RIs standby solution for the new OSS will be implemented to enable the reconfiguration of wireless topology.

By integrating EEOM with EATC, both wireless and optical components are utilized more efficiently. Thus, the energy efficiency of the FiWi network is improved significantly.

## 2 Related work

The energy savings techniques have been studied well for PON. Generally, theses research efforts aim to reduce the energy consumption of ONUs by means of either energy-efficient component development [10, 11] or ONU sleep mechanism [12–14].

Ref. [10] studied the power consumption model of various transceivers and the expected performance of the advanced electronic and photonic devices. Ref. [11] proposed to eliminate the buffers from the ONUs because buffer is a significant energy-consuming source. Instead, the end nodes will use their additional memory to buffer the packets locally. Ref. [12] proposed two MAC protocols based on fixed bandwidth allocation for energy savings in Ethernet PONs (EPON). Ref. [13] proposed a Service-Level-Agreement (SLA) based scheduling scheme for PON. According to this scheme, the ONU can quit sleep process before the predetermined end time of sleep in order to send high-priority packets with strict SLA. Ref. [14] put the components of ONU into sleep state and enable multiple-power-level ONU. The energy savings schemes based on multiple-power-level ONU were proposed for different scenarios.

Most of the above-mentioned papers may be extended to FiWi for the energy savings in the optical back-end. However, according to them, the ONUs have to experience frequent state switching due to the delay requirement of data packet, which is not preferable for the energy savings in FiWi. Therefore, it is necessary to develop energy savings techniques for FiWi.

Ref. [15] addressed the building of green FiWi network by means of ONU sleep and energy-aware routing. Ref. [16] presented an overview of the energy-efficient protocols and approaches in the FiWi network. Ref. [17] aimed at the tradeoff between energy savings and QoS in Energy Efficient Ethernet (EEE)-based FiWi. Ref. [18] addressed a comprehensive approach to the energy savings in the optical access network integrated with in-house wireless network. A project called Customer Premises Equipment for Low-power and Low-cost Architectures (CUPELLA) was developed to study the energy-efficient access technologies.

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

In summary, the previous works [15-18] mostly focus on the energy savings in the optical back-end of FiWi by combining ONU sleep mechanism with wireless rerouting. However, most of the works do not consider the energy savings in the wireless front-end. It will be promising for higher energy efficiency in FiWi if integrating wireless and optical energy savings techniques.

## 3 Network architecture

To support the WOES scheme, we set a FiWi architecture composed of multi-radio WMN as the wireless front-end and EPON as the optical back-end. Each ONU drives a wireless gateway by wired cable to act as the interface between wireless front-end and optical back-end.

In the optical back-end, all ONUs share the single upstream wavelength as well as downstream wavelength by using Time Division Multiplexing (TDM) [12]. In terms of the upstream transmission, the optical back-end is a multi-point media access network, where the Multi-Point Control Protocol (MPCP) is used in the MAC layer to handle the bandwidth contention among ONUs. In terms of the downstream transmission, the optical back-end is a broadcast network, where each data packet from OLT is broadcasted to all ONUs through the splitter. Each ONU will determine to either accept or discard the data packet according to whether the destination address is matched [14]. All ONUs are equipped with the sleep functionality.

In the wireless front-end, each wireless node (e.g., wireless router or wireless gateway) is configured with multiple RIs and the number of RIs varies across different wireless nodes [19,20]. Each RI goes into standby or active state according to the network demand. The wireless link, which is designated by a pair of end RIs in different wireless nodes, is bidirectionally available only if both end RIs are active. Therefore, the wireless topology in the front-end depends on the states of all RIs over the whole network.

When the end user wants to connect to Internet, it first sends a connection request to its primary wireless router. Then, the wireless router will compute a wireless path to one of the active ONUs which will be the destination ONU for this connection request. Thereafter, the end user can transmit the data packets into its destination ONU along the wireless path. Thus, the ONUs are responsible for collecting the traffic from different wireless routers and sending the traffic to the OLT through the optical back-end. Finally, the OLT will transmit the traffic into Internet.

To the best of our knowledge, the integrated structure of ONU and wireless gateway has not been standardized. Especially, the functionality of ONU sleep and RI standby in an integrated structure remains to be developed. For the application in current industry, we consider the independent structure of ONU and wireless gateway in this paper. However, the proposed WOES scheme can be easily extended to the integrated structure of ONU and wireless gateway if such an integrated structure is available.

## 4 Proposed WOES scheme

In this section, we first introduce the notation of the proposed WOES scheme. Then, we elaborate on the interactive modules EEOM and EATC in the WOES scheme.

### 4.1 Notation

**Given.**

- $N_{\mathrm{WN}}$: number of wireless nodes in the network, including wireless routers and wireless gateways.
- $x$: index of wireless node, $x \in \{1, 2, 3, \ldots, N_{\mathrm{WN}}\}$.
- $S_R$: set of wireless router indices. $|S_k|$ is the number of wireless routers in the network.
- WN-$x$: wireless node indexed by $x$. Particularly, $\forall x \in S_R$ , WN$-x$ denotes the wireless router.
- $N_O$: number of ONUs in the network.
- $i$: index of ONU, $i \in \{1, 2, 3, \ldots, N_O\}$.
- ONU-i: ONU indexed by $i$.
- $w$: index of ONU State Set (OSS), $w \in \{1, 2, 3, \ldots, 2^{N_O} - 1\}$.

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

- $N_{\mathrm{RI}}$: number of RIs in the network.
- $k$: index of RI, $k \in \{1, 2, 3, \ldots, N_{\mathrm{RI}}\}$.
- RI-$k$: RI indexed by $k$.
- $N_{\mathrm{RI}}^x$: number of RIs in WN-$x$.
- $\mu_x^k$: binary constant, taking 1 if RI-$k$ is attached to WN-$x$, and 0 otherwise.
- $H_{x,i}^w$: length of the shortest wireless path (measured in hops) from the wireless router WN-$x$ ($x \in S_R$) to the wireless gateway connected with the active ONU-$i$ when all RIs in the network are active for the $w$th OSS.
- $H_x^w$: length of the shortest wireless path from the wireless router WN-$x$ ($x \in S_R$) to the wireless gateway connected with any active ONU when all RIs in the network are active for the $w$th OSS, that is, $H_x^w = \min\{H_{x,i}^w, \forall i\}$.
- $\overline{H^w}$: average length of the shortest wireless path from each wireless router to the wireless gateway connected with any active ONU when all RIs in the network are active for the $w$th OSS. $\overline{H^w}$ is calculated in Eq.(5).
- $P_{\max}^x$: maximum power consumption of WN-$x$ when all $N_{\mathrm{RI}}^x$ RIs are active.
- $P_{\mathrm{ARI}}$: power consumption of an active RI.
- $P_{\mathrm{ARI}}$: power consumption of a standby RI.
- $P_{\mathrm{AONU}}$: power consumption of an active ONU.
- $P_{\mathrm{SONU}}$: power consumption of a sleeping ONU.

**Variables.**

- $\lambda_k$: binary indicator of RI state, taking 1 if RI-$k$ is in the active state and 0 otherwise.
- $N_{\mathrm{ARI}}^x$: umber of active RIs in WN-$x$, where $N_{\mathrm{ARI}}^x \leqslant N_{\mathrm{RI}}^x$.
- $P(N_{\mathrm{ARI}}^x)$: power consumption of WN-$x$ with $N_{\mathrm{ARI}}^x$ active RIs.
- $\theta_{x,i}^w$: binary variable, taking 1 if WN-$x$ has at least one wireless path to the active ONU-$i$ according to the RIs standby solution for the $w$th OSS, and 0 otherwise.
- $h_{x,i}^w$: length of the shortest wireless path from the wireless router WN-$x$ ($x \in S_R$) to the wireless gateway connected with the active ONU-$i$ according to the RIs standby solution for the $w$th OSS, where $h_{x,i}^w \geqslant H_{x,i}^w$.
- $h_x^w$: length of the shortest wireless path from the wireless router WN-$x$ ($x \in S_R$) to the wireless gateway connected with any active ONU according to the RIs standby solution for the $w$th OSS, where $h_x^w = \min\{h_{x,i}^w, \forall i\}$ and $h_x^w \geqslant H_x^w$.
- $\overline{h^w}$: average length of the shortest wireless path from each wireless router to the wireless gateway connected with any active ONU according to the RIs standby solution for the $w$th OSS, where $\overline{h^w}$ is calculated in Eq.(6) and $\overline{h^w} \geqslant \overline{H}^w$.
- $R_x^w$: set of RI indices on the shortest wireless path from the wireless router WN-$x$ ($x \in S_R$) to the wireless gateway connected with any active ONU according to the RIs standby solution for the $w$th OSS.

### 4.2 EEOM: energy savings in optical back-end

In our WOES scheme, we develop the EEOM module for the energy savings in the optical back-end of FiWi. According to EEOM, the OLT will maintain a pair of thresholds LT and HT to control the ONU state. Each ONU needs to transmit the bandwidth request to the OLT periodically. The bandwidth request is an indicator for the traffic load of the ONU. Thus, the OLT has the knowledge of the traffic load of all ONUs in the network. In a periodic way, the OLT will iteratively detect the active ONU, e.g., ONU-$i$, whose normalized traffic load is lower than or equal to LT and transmit the sleep trigger signal to it. Upon receiving the sleep trigger signal from OLT, ONU-$i$ will first broadcast the sleep notification to its source wireless routers whose traffic is sent to ONU-$i$, and then ONU-$i$ goes into sleep state. Accordingly, the source wireless routers of ONU-$i$ need to reroute their traffic to other active ONUs. When any active ONU has the normalized traffic load higher than or equal to HT, one of the sleeping ONUs will be activated in order to alleviate the traffic load of the active ONUs and prevent them from traffic overflow.

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

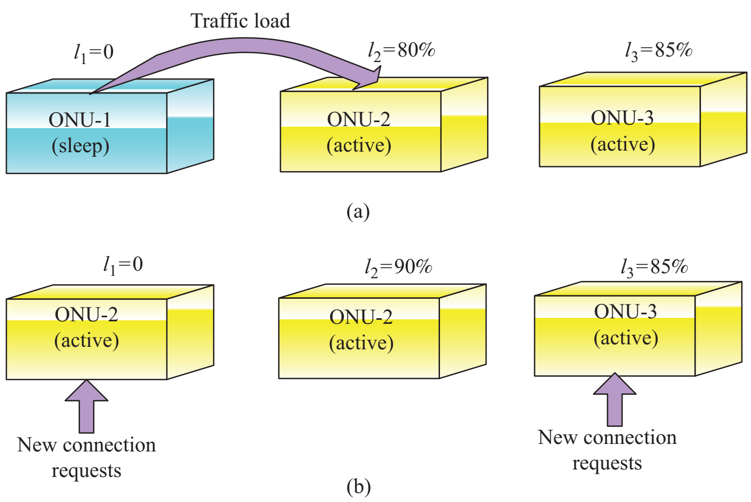


**Figure 2** (Color online) Illustration of LT and HT in the EEOM module (LT=10% and HT=90%). (a) Putting ONU-1 into sleep state (current period); (b) putting ONU-1 into active state (next period).

For example, we assume three ONUs in the FiWi network, ONU-1, ONU-2 and ONU-3 carrying the normalized traffic load $l_1$ =10%, $l_2$ =70% and $l_3$ =85%, respectively. All three ONUs have the same capacity. As shown in Figure 2(a), assuming LT=10% and HT=90%, OLT will trigger ONU-1 into sleep state because $l_1 \leqslant$ LT. The connections in ONU-1 will be rerouted to the active ONU-2 with the shortest path criterion. Accordingly, the traffic load of ONU-1 is transferred into ONU-2 with $l_1 = 0$ and $l_2$ =80% as a result. When the normalized traffic load of ONU-2 reaches 90% at the next period, i.e., $l_2 = 90\% \geqslant$ HT, the sleeping ONU-1 will be activated to carry the new connection requests as shown in Figure 2(b). The new connection requests will not be sent to ONU-2 until $l_2 <$ HT.

It should be noted that each ONU according to EEOM has two alternative states, i.e., sleep or active. The states of all ONUs in the network constitute an OSS. We introduce a binary indicator for the state of each ONU, taking 1 if the ONU is active and 0 otherwise. Thus, in the case of $N_O$ ONUs, each OSS can be represented as a group of $N_O$ binary numbers. For example, in the FiWi network including 3 ONUs, there are totally 7 OSSs excluding the "000" (i.e., all three ONUs are sleeping).

By means of EEOM, the ONU will be utilized more efficiently, which helps reduce the energy consumption of the optical back-end. However, when one or more ONUs in the network is/are sleeping, the connections will be routed to the active ONUs by using only a part of RIs in the wireless front-end. Many other RIs will remain idle and cause the waste of much energy. Therefore, there is a potential opportunity for higher energy efficiency of FiWi if the wireless energy savings is taken into account.

### 4.3 EATC: energy savings in wireless front-end

Aiming at the energy savings in the wireless front-end, we develop another module EATC in the WOES scheme to put the idle RIs into standby state as more as possible. In this subsection, we first state the optimization problem of RIs standby in EATC. Then, we propose the Genetic Algorithm (GA) based approach for this optimization problem.

#### 4.3.1 *Problem statement*

As mentioned previously, the configuration of wireless topology is determined by the RIs standby solution over the whole network, i.e., $\{\lambda_k, \forall k\}$ . More standby RIs bring about lower power consumption of the wireless front-end. However, this will also undermine the connectivity of the wireless topology in the front-end. In the case of the $w$th OSS $\forall w$, the RIs standby solution should ensure that each wireless router WN-$x(x \in S_R)$ can connect to at least one active ONU with all RIs on the wireless path between them active (i.e., the traversed links are available). Thus, the connection requests from WN-$x(x \in S_R)$ will not be blocked due to the unavailable wireless path to the active ONU. For this consideration, we introduce the constraint of connectivity for the $w$th OSS into EATC as follows:

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

**Constraint of connectivity.**

$$\sum_{i=1}^{N_O} \theta_{x,i}^{w} \geqslant 1, \quad \forall x \in S_R, \forall w, \tag{1}$$

$$\sum_{k \in R_x^w} = |R_x^w|, \quad \forall x \in S_R, \forall w. \tag{2}$$

According to the constraint of connectivity, the wireless router WN-$x(x \in S_R)$ should have at least one active RI. Thus, we can further introduce the constraint of active RI number into EATC as follows:

**Constraint of active RI number.**

$$1 \leqslant N_{\mathrm{ARI}}^{x} \leqslant N_{\mathrm{RI}}^{x}, \quad \forall x \in S_R, \tag{3}$$

$$N_{\mathrm{ARI}}^{x} = \sum_{k=1}^{N_{\mathrm{RI}}} \mu_x^k \lambda_k, \quad \forall x \in S_R. \tag{4}$$

Considering the end-to-end delay requirement, we also introduce the constraint of wireless path length into EATC. It should be noted that, when all RIs in the network are active, each wireless router WN-$x(x \in S_R)$ has the shortest wireless path to the wireless gateway connected with any active ONU in the case of the $w$th OSS. Thus, the average length of the shortest wireless path $\overline{H^w}$ is calculated as

$$\overline{H^w} = \frac{1}{|S_R|} \sum_{x \in S_R} H_x^w, \quad \forall w. \tag{5}$$

where $H_x^w$ can be calculated by using the shortest path routing algorithm such as Dijkstra. Based on Eq.(5), we can describe the constraint of wireless path length in EATC as follows.

**Constraint of wireless path length.** In the case of the $w$th OSS, the RIs standby solution should guarantee that all wireless routers can connect to the active ONUs with the average length of the shortest wireless path as

$$\overline{h^w} = \frac{1}{|S_R|} \sum_{x \in S_R} h_x^w \leqslant \lfloor c \cdot \overline{H^w} \rfloor, \quad \forall w, \tag{6}$$

where $c \geqslant 1$ denotes the hop number coefficient.

When the OSS of the network varies, the current wireless topology may not support the network demand under the constraints in Eqs.(1)–(6). It is necessary to reconfigure the wireless topology for the new OSS by changing the states of the RIs in the network. Therefore, we need to compute the RIs standby solution and the resulting wireless topology for each OSS. Under the constraints in Eqs.(1)–(6), we compute the RIs standby solution with the objective of minimizing the energy consumption of wireless front-end as follows,

**Objective.**

$$\text{Minimize} \sum_{x=1}^{N_{\mathrm{WN}}} P(N_{\mathrm{ARI}}^{x}), \tag{7}$$

$$P(N_{\mathrm{ARI}}^{x}) = P_{\max}^{x} - (N_{\mathrm{RI}}^{x} - N_{\mathrm{ARI}}^{x}) \cdot (P_{\mathrm{ARI}} - P_{\mathrm{SRI}}), \quad \forall x, \tag{8}$$

where Eq.(8) formulates the power consumption model of the wireless node WN-$x$ with $N_{\mathrm{ARI}}^{x}$ active RIs. According to this power consumption mode, each wireless router also has other energy-consuming components except RIs.

The OLT will maintain a map of OSSs to RIs standby solutions, i.e., OSS map. Once the OSS of the network varies, the OLT first determines the RIs standby solution for the new OSS according to the OSS map, and then it broadcasts the determination of the RIs standby solution to all ONUs through the splitter. The ONUs need to forward the RIs standby solution to all of wireless routers. According to the received RIs standby solution, each wireless router will update the states of its RIs to enable the reconfiguration of wireless topology.

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

In the above optimization problem, it is difficult to describe the linear constraints regarding the variables $\theta_{x,i}^{w}$, $h_{x}^{w}$ and $\lambda_k$, $\forall i, w, x, k$. We have to use the shortest path routing algorithm to compute $\theta_{x,i}^{w}$ and $h_{x}^{w}$ in the wireless topology determined by $\lambda_k$. Therefore, the optimization problem of RIs standby is basically a nonlinear one, which is computationally infeasible to use the Integer Linear Programming (ILP) approach.Furthermore, the problem of RIs standby for wireless topology reconfiguration has been proven to be NP-hard [2], because this problem can be reduced to a Generalized Assignment Problem (GAP). It is necessary to develop an algorithmic approach.

#### 4.3.2 *GA based approach*

GA has been demonstrated to be an efficient approach to solve the nonlinear optimization problem [21,22]. For the first time, we propose a GA based approach to compute the best RIs standby solution for each OSS in EATC. Given the $w$th OSS, the proposed GA represents each of the RIs standby solutions for the $w$th OSS as an individual. We iteratively implement the genetic operators including selection, crossover and mutation on the parent individuals to bear the new individuals. The new individuals usually have higher fitness than that of the parent individuals. Thus, the RIs standby solution for the $w$th OSS will evolve towards better with lower wireless energy consumption. Finally, we obtain the best RIs standby solution for the $w$th OSS when the iteration of GA terminates. For simplicity of presentation, we first introduce the notation used in the proposed GA as follows.

- $N_P$: number of populations.
- $m$: index of population, $m \in \{1, 2, 3, \ldots, N_P\}$.
- $P_m$: the $m$th population.
- $N_I$: population size.
- $n$: index of individual, $n \in \{1, 2, 3, \ldots, N_I\}$.
- $I_m^n$: the $n$th individual in the population $P_m$. $I_m^n$ is an array of $N_{\rm RI}$ binary elements and each element represents a gene.
- $\lambda_{m,n}^{k}$: the $k$th gene of $I_m^n$, taking 1 if *RI-k* is in the active state and 0 otherwise.
- $f(I_m^n)$: fitness of $I_m^n$.
- $p_{\rm sel}^{m,n}$: selection probability of $I_m^n$.
- $p_{\rm cro}$: crossover probability.
- $p_{\rm mut}$: mutation probability.

**Individual and population.** In the proposed GA, we formulate the individual $I_m^n$ as follows,

$$I_m^n = \left[\lambda_{m,n}^{1},\ \lambda_{m,n}^{2},\ \lambda_{m,n}^{3}, \ldots,\ \lambda_{m,n}^{N_{\rm RI}}\right], \quad \forall m, n. \tag{9}$$

Given $I_m^n$, we can calculate the indicator of RI state $\lambda_k = \lambda_{m,n}^{k}$ $\forall k$ and the resulting wireless topology. According to the wireless topology of $I_m^n$, we can further calculate the variables $N_{\rm ARI}^{x}$, $\theta_{x,i}^{w}$ and $h_x^w$ and $R_x^w$. $I_m^n$ should satisfy the constraints in Eqs.(1)–(6) so as to represent a feasible RIs standby solution for the $w$th OSS. We refer to the individual satisfying the constraints in Eqs.(1)–(6) as the available individual. $N_I$ available individuals constitute a population. Particularly, the $m$th population is formulated as

$$P_m = \{I_m^n | n \in \{1, 2, 3, \ldots, N_I\}\}, \quad \forall m, n. \tag{10}$$

where $I_m^n$ $\forall n$ satisfies the constraints in Eqs.(1)–(6). Without loss of generality, the initial population $P_1$ is generated by randomly creating $N_I$ available individuals.

**Fitness function.** We evaluate the fitness of available individuals according to the fitness function. In the proposed GA, the fitness function should be defined in such a way that the fitter individual (i.e., individual with higher fitness) can yield better RI standby solution. Here, a better RI standby solution will bring about a lower energy consumption of the wireless front-end. Thus, we can define the fitness function as follows:

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

$$f(I_m^n) = \frac{\Psi}{\sum_{x=1}^{N_{\rm WN}} P(N_{\rm ARI}^{x})}, \quad \forall m, n. \tag{11}$$

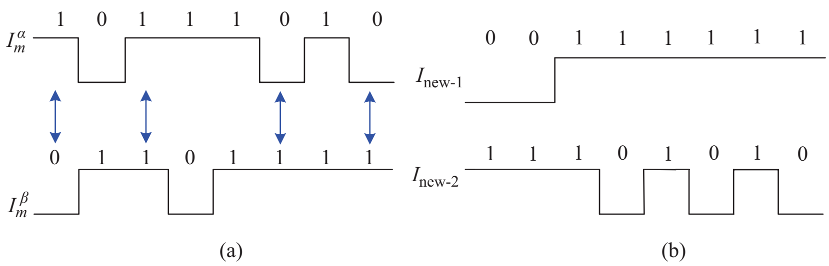


**Figure 3** (Color online) Illustration of the uniform crossover operator. (a) Parent individuals; (b) new individuals.

$$\Psi = \sum_{x=1}^{N_{\text{WN}}} P_{\max}^x. \tag{12}$$

where $\Psi$ is the maximum power consumption of the wireless front-end when all RIs are active. Therefore, the fitness $f(I_m^n)$ is always greater than or equal to 1. Higher fitness means lower energy consumption of the wireless front-end.

**Genetic operators.** The evolution is carried out to create new population by implementing the genetic operators including selection, crossover and mutation on the current population. It has been demonstrated in [22,23] that the combination of roulette wheel selection and uniform crossover can significantly improve the performance of GA. Thus, we use such combination in the proposed GA to produce the better solution. Specifically, we first use the roulette wheel method [22] to select $\lfloor N_I/2 \rfloor$ individuals from $P_m$ and copy them into $P_{m+1}$. The individual $I_m^n$ is selected with the probability

$$p_{\text{sel}}^{m,n} = \frac{f(I_m^n)}{\sum_{y=1}^{N_I} f(I_m^y)}, \quad \forall m, n. \tag{13}$$

Then, we further select two fittest individuals $I_m^\alpha$ and $I_m^\beta$ as a pair of parent individuals. Other $\lceil N_I/2 \rceil$ individuals in $P_{m+1}$ will be created by implementing the crossover and mutation operators on $I_m^\alpha$ and $I_m^\beta$.

As the uniform crossover [23], we randomly generate an array of mask codes $M = [m_1, m_2, \ldots, m_{N_{\text{RI}}}]$. Each element in $M$ takes 0 or 1 randomly. Based on $M$, we can implement the uniform crossover on $I_m^\alpha$ and $I_m^\beta$ to generate a pair of new individuals $I_{\text{new-1}} = [\lambda_{\text{new-1}}^1, \lambda_{\text{new-1}}^2, \ldots, \lambda_{\text{new-1}}^{N_{\text{RI}}}]$ and $I_{\text{new-2}} = [\lambda_{\text{new-2}}^1, \lambda_{\text{new-2}}^2, \ldots, \lambda_{\text{new-2}}^{N_{\text{RI}}}]$ as follows. We first copy $I_m^\alpha$ and $I_m^\beta$ to $I_{\text{new-1}}$ and $I_{\text{new-2}}$, respectively. Then, with the crossover probability $p_{\text{cro}}$, we exchange the $k$th gene between $I_{\text{new-1}}$ and $I_{\text{new-2}}$ only if $m_k = 1$ $\forall k$. For example in Figure 3(a), both $I_m^\alpha$ and $I_m^\beta$ are assumed to be the arrays of eight genes. Assuming $M = \{1, 0, 1, 0, 0, 1, 0, 1\}$, we can implement the uniform crossover on $I_m^\alpha$ and $I_m^\beta$ to generate the new individuals $I_{\text{new-1}}$ and $I_{\text{new-2}}$ as shown in Figure 3(b). It should be noted that, if both $I_{\text{new-1}}$ and $I_{\text{new-2}}$ are not available individuals, we will regenerate the mask codes until the available $I_{\text{new-1}}$ and $I_{\text{new-2}}$.

To avoid the local optimum, we also apply the mutation operator to change the gene structure of $I_{\text{new-1}}$ and $I_{\text{new-2}}$ with the mutation probability $p_{\text{mut}}$. In terms of $I_{\text{new-1}}$, we implement the mutation on it to generate $I'_{\text{new-1}}$ by randomly selecting two genes and exchanging them [23]. In a similar way, we can implement the mutation on $I_{\text{new-2}}$ to generate $I'_{\text{new-2}}$ . For the available individuals, we ensure $I'_{\text{new-1}}$ and $I'_{new\text{-}2}$ to satisfy the constraints in Eqs.(1)–(6). Thereafter, $I'_{\text{new-1}}$ and $I'_{\text{new-2}}$ will be added into $P_{m+1}$ as the new individuals. We use such mutation operator for the purpose of simplicity. However, there may be other alternative mutation operators for better performance of the proposed GA.

**Elitism method.** With the genetic operators above, the new individuals are continuously generated until the population $P_{m+1}$ is fully created. For higher fitness of the individuals in $P_{m+1}$, we introduce the elitism method [22] into the proposed GA. According to the elitism method, we need to compare all individuals in $P_m$ and $P_{m+1}$ and choose the fittest $N_I$ individuals as $P_{m+1}$. The elitism method can prevent the loss of the fittest individuals during evolution, thus contributing to the best RI standby solution.

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

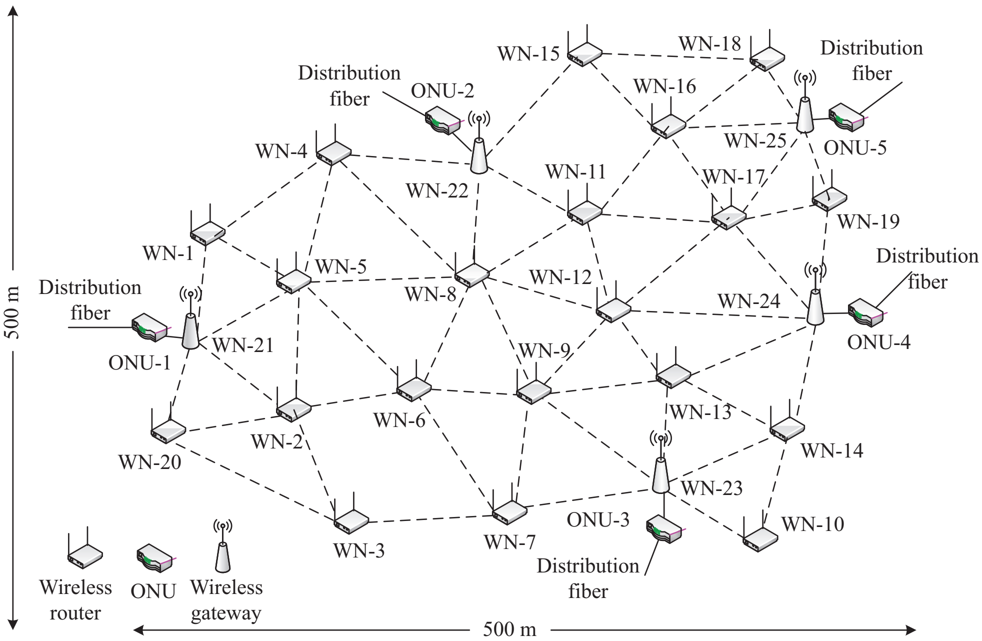


**Figure 4** (Color online) Simulated FiWi network.

We continuously create the new populations until the number of populations reaches $N_P$ which is the termination criterion of the proposed GA. Finally, we can obtain the fittest individual $I^{\alpha}_{N_P}$ from the last population. It is expected that $I^{\alpha}_{N_P}$ yields a best RIs standby solution $\lambda_k = \lambda^k_{m,n}$ $\forall k$ for the $w$th OSS. Due to the space limitation, we omit the pseudo-code procedure of the proposed GA in this paper.

## 5 Performance evaluation

### 5.1 Network setting

In the simulation, we set a FiWi network in an area of 500 m × 500 m. As shown in Figure 4, the network consists of 5 ONUs, 5 wireless gateways and 20 wireless routers. In the wireless front-end, the wireless nodes (i.e., wireless routers and wireless gateways) are placed according to the SFNet [9]. Each wireless node has a transmission range of 125 m and an interference range of 250 m [19]. We randomly configure 1, 2, 3 or 4 RIs for all wireless routers. All wireless gateways are uniformly configured with 4 RIs. The IEEE 802.11a standard is applied for the implementation of WMN. Thus, there are 12 non-overlapping channels and each channel has a bandwidth capacity of 54 Mb/s [20]. We select 8 non-overlapping channels and randomly assign them to the RIs over the whole network. It is guaranteed that each wireless node has at least two neighbor nodes. Each pair of neighbor wireless nodes is located in the transmission range of each other and has the common channel. The capacity of wireless links are determined by the given link scheduling. In the optical back-end, we deploy the IEEE 802.3ah EPON with the distribution fiber length of 5 km and the feeder fiber length of 15 km. Each ONU is connected to a wireless gateway by wired cable and allocated the bandwidth capacity of 50 Mb/s for upstream and downstream transmission, respectively. These five ONUs integrated with wireless gateways are used as the interface between wireless front-end and optical back-end of the simulated FiWi network. Furthermore, we assume that the sleeping ONU takes 3.5 ms to switch into the active state, and the standby RI takes 5 ms to switch into the active state. In the process of switching state, the ONU and RI have the power consumption equal to that of their active state, respectively [2]. All wireless nodes and ONUs are assumed to have infinite buffer size [8]. Thus, the data packets in the simulated FiWi network will not be dropped due to the buffer overflow.

### 5.2 Traffic model

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

We set a dynamic traffic model in the simulated FiWi network and implement it for 1000 s [24]. In this model, the matrix of connection requests is unknown in advance. All connection requests enter into the

**Table 1** Setting of power consumption parameters (part I) [2, 13]

| ONU | | RI | |
|---|---|---|---|
| Active ($P_{\mathrm{AONU}}$) | Sleep ($P_{\mathrm{SONU}}$) | Active ($P_{\mathrm{ARI}}$) | Standby ($P_{\mathrm{SRI}}$) |
| 3.85 W | 0.75 W | 1.2 W | 0.18 W |

**Table 2** Setting of power consumption parameters (Part II) [7]

| Wireless node with all $N^x_{\mathrm{RI}}$ RIs active ($P^x_{\max}$) | | | |
|---|---|---|---|
| $N^x_{\mathrm{RI}}$=1 | $N^x_{\mathrm{RI}}$=2 | $N^x_{\mathrm{RI}}$=3 | $N^x_{\mathrm{RI}}$=4 |
| 1.85 W | 3.05 W | 4.30 W | 5.50 W |

**Table 3** Setting of GA parameters [22,23]

| $N_{\mathrm{I}}$ | $N_{\mathrm{P}}$ | $p_{\mathrm{cro}}$ | $p_{\mathrm{mut}}$ |
|---|---|---|---|
| 100 | 2000 | 0.9 | 0.15 |

network according to Poisson process with the average arrival rate $\lambda$ (connection requests per second). The duration of connection follows the exponential distribution with the mean $1/\mu$(seconds). The network load is measured in $\lambda/\mu$ Erlang. We simulate each connection as a Constant-Bit-Rate (CBR) flow, which generates the packets at the rate of 125 packets per second with the packet size of 1000 bytes. Thus, the flow rate is 1 Mb/s. We consider the upstream and downstream traffic together. The number of upstream connection requests is half that of downstream connection requests. All upstream connection requests are sent to the OLT and each one is randomly designated a source wireless router. All downstream connection requests originate from the OLT and each one is randomly designated a destination wireless router. The shortest path routing algorithm is used to calculate the route for each connection request when it enters into the network. Thereafter, the connection is established and will not depart from the network until its duration ends. Upon the departure of a connection, the network resource (i.e., radio capacity and ONU capacity) occupied by this connection will be released.

### 5.3 Parameters setting

We set the power consumption parameters and GA parameters in Tables 1–3, respectively.

### 5.4 Results and analysis

Based on the simulation setting above, we evaluate the performance of the proposed WOES scheme and compare it with the No Energy Savings (NES) scheme and the Optical Energy Savings (OES) scheme [15]. The NES scheme does not apply any energy savings mechanism. The OES scheme focuses on the energy savings only in the optical back-end of FiWi by using ONU sleep mechanism. The details are as follows.

**ONU sleep ratio.** In Figure 5, given the hop number coefficient $c = 1.5$ (see (6)), we show the results of ONU sleep ratio versus network load. Here, the ONU sleep ratio is defined as the ratio of sleep period to simulation duration for each ONU on average. Higher ONU sleep ratio means better performance in energy savings in optical back-end. The NES scheme has zero ONU sleep ratio because it does not consider the ONU sleep functionality. In comparison, the OES and WOES schemes exhibit considerable ONU sleep ratio because both of them implement the ONU sleep mechanism by using a pair of thresholds. However, our WOES scheme also considers the RI standby mechanism which results in the different wireless topology from the OES scheme. Thus, we observe that OES and WOES have different ONU sleep ratio for the given LT and HT. When network load increases, each ONU will carry more traffic load at any given time and thus experiences shorter sleep period. As a result, both OES and WOES schemes have a decreasing ONU sleep ratio. However, their ONU sleep ratio is never lower than 16.1% when LT=10%, HT=80% and network load varies from 1 Erlang to 8 Erlang. Furthermore, in the case of higher LT and higher HT, each ONU can switch into the sleep state more frequently and enjoy longer sleep period. Therefore, we observe that OES and WOES have higher ONU sleep ratio in the case of higher LT and higher HT. For example, when network load varies from 5 to 8 Erlang, WOES (LT=25%, HT=95%) achieves an increment of 37.5% in ONU sleep ratio over WOES (LT=10%, HT=80%).

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

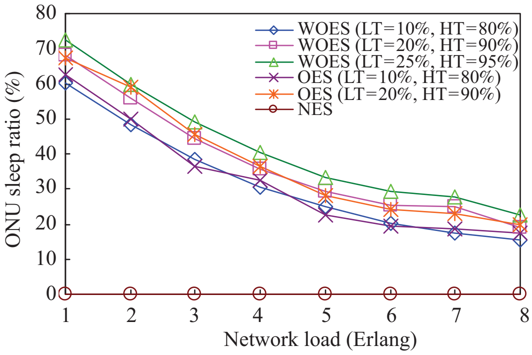


**Figure 5** (Color online) ONU sleep ratio vs. network load.

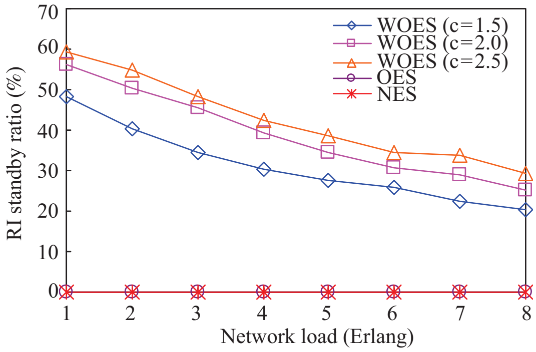


**Figure 6** (Color online) RI standby ratio vs. network load.

**RI standby ratio.** In Figure 6, given LT=10% and HT=80%, we investigate the performance of WOES in the RI standby ratio under different network loads. RI standby ratio is defined as the ratio of standby period to simulation duration for each RI on average. Higher RI standby ratio indicates better energy savings in the wireless front-end. Both NES and OES schemes exhibit zero RI standby ratio because they do not cover wireless energy savings. In our WOES scheme, we enable the energy savings in the wireless front-end by putting the idle RIs into standby state. It is observed that WOES realizes a significant RI standby ratio, especially in the case of larger hop number coefficient $c$. The reason is that, when $c$ is larger, fewer wireless links are required to be available for satisfying the constraint of wireless path length. In this case, more RIs are put into standby state and each RI enjoys longer standby period, hence higher RI standby ratio. With the network load increasing, each RI will remain active for a longer time in order to carry more connections. As a result, the RI standby ratio of WOES gradually decreases. However, it is never lower than 21.3% when $c = 1.5$ and network load varies from 1 Erlang to 8 Erlang.

**Average energy consumption.** In Figure 7, we compare the WOES scheme with the NES and OES schemes in terms of average energy consumption. Here, the average energy consumption is defined as the energy consumed by all ONUs and wireless routers in the whole network per second. Thus, the average energy consumption (Joule per second) has the same physical meaning as the power consumption (Watt) [16, 17]. The NES scheme does not introduce any energy savings mechanism. Thus, it produces the maximum energy consumption which can be used as a baseline to evaluate the performance gain of OES and WOES. As mentioned in the analysis of Figures 5 and 6, both OES and WOES schemes reduce the energy consumption of FiWi by improving the utilization of network resource. Particularly, our WOES scheme shows the best performance because it aims at the energy savings in both wireless front-end and optical back-end. For example, compared to the maximum energy consumption from NES, WOES (LT=10%, HT=80%, $c$=1.5) can save more than 17.1% energy even when network load varies from 5 Erlang to 8 Erlang. Hereby, WOES (LT=10%, HT=80%, $c$=1.5) gains the performance improvement of more than 12.2% over OES (LT=20%, HT=90%). As expected, WOES can achieve better energy savings in the case of higher LT, higher HT and larger $c$.

**Average end-to-end delay.** In Figure 8, we investigate the performance of the WOES scheme in average end-to-end delay and compare it with the NES and OES schemes. Here, we define the average end-to-end delay as the time that each packet goes from source node to destination node on average, including all queuing delay and transmission delay. With the network load growing, all three schemes show the gradually increasing average end-to-end delay. In the OES and WOES schemes, the ONU sleep mechanism encourages more connections to share the active ONUs, such that more low-load ONUs can be put into sleep state for energy savings. As a result, each connection is allocated less bandwidth capacity, which causes larger transmission delay in ONUs. Thus, we observe that the OES and WOES schemes exhibit larger average end-to-end delay than the NES scheme. In the WOES scheme, RIs standby diminishes the connectivity of wireless topology in the front-end. Each connection has to transfer its traffic through the longer wireless path and thus experiences larger delay for wireless transmission. Therefore,

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

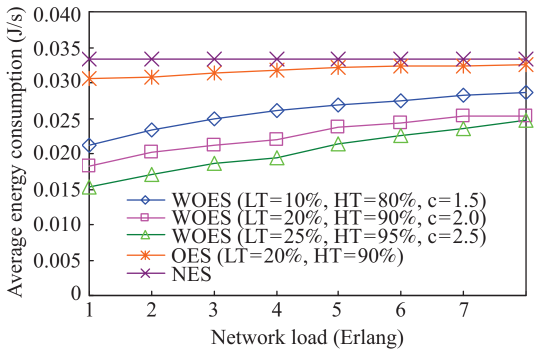


**Figure 7** (Color online) Average energy consumption vs. network load.

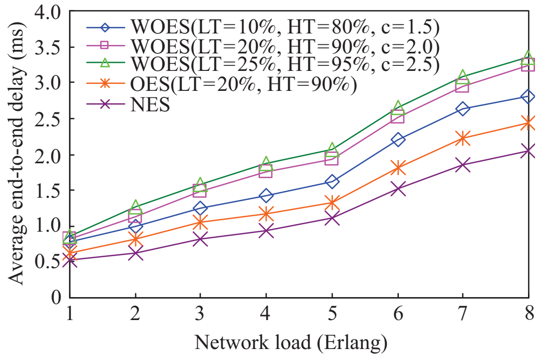


**Figure 8** (Color online) RI Average end-to-end delay vs. network load.

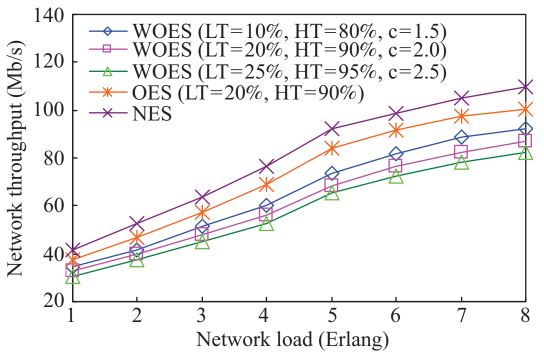


**Figure 9** (Color online) Network throughput vs. network load.

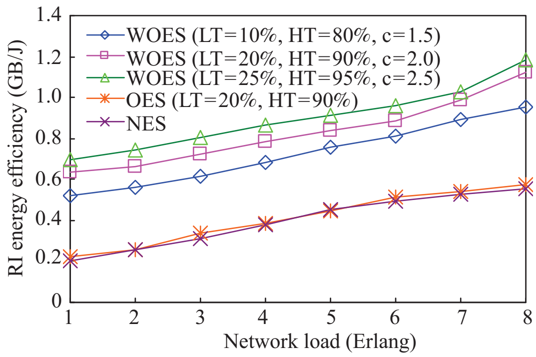


**Figure 10** (Color online) RI energy efficiency vs. network load.

we observe that WOES has larger average end-to-end delay than OES, especially in the case of higher LT, higher HT and larger c. However, due to the constraint of wireless path length, WOES does not show too much performance degradation in average end-to-end delay. For example, compared with OES (LT=20%, HT=90%), the performance degradation of WOES (LT=10%, HT=80%, $c$=1.5) remains lower than 14.7% even when network load varies from 5 Erlang to 8 Erlang.

**Network throughput.** In Figure 9, we show the results of network throughput versus network load for different schemes. We define the network throughput as the ratio of total traffic successfully transmitted over the simulation duration. When the network load increases, there will be more connections requests poured into network for per unit of time. Thus, all of three schemes have the growing network throughput with the network load increasing. However, we experimentally observe that the network throughput begins to converge towards a constant level when the network load increases over the network capacity. As addressed in the analysis of Figure 8, the WOES scheme makes the packets experience longer end-to-end delay than the NES and OES schemes. Hence, there is less traffic successfully transmitted to the destination nodes during the simulation, which causes lower network throughput of WOES. However, the constraint of wireless path length prevents WOES from too much loss of network throughput. For example, the network throughput of WOES (LT=10%, HT=80% and $c$=1.5) is never lower than 88.2% of the network throughput of OES (LT=20%, HT=90%) when network load varies from 5 to 8 Erlang.

**RI energy efficiency.** In Figure 10, we compare the WOES scheme with the NES and OES schemes in terms of RI energy efficiency. Here, we compute the RI energy efficiency as the ratio of traffic volume to energy consumption for each RI on average. Thus, RI energy efficiency (GB/J, i.e., Gigabyte per Joule) denotes the traffic volume supported by per unit of energy, which is also a proportional indicator of the throughput achieved by per unit of power (Gb/s/W). It is notable that larger traffic volume and shorter active period of RI contribute to higher RI energy efficiency. In the NES and OES schemes, all RIs remain active over the whole simulation duration regardless of network load. Each RI will transmit and receive

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

more traffic when the network load increases. Thus, we observe that the NES and OES schemes have an increasing RI energy efficiency with the network load increasing. However, the RI energy efficiency of both schemes is never higher than 0.57 GB/J. In comparison, the WOES scheme brings about notably higher RI energy efficiency than NES and OES by using RI standby mechanism, especially in the case of higher LT, higher HT and larger c. For example, when the network load varies from 5 to 8 Erlang, the RI energy efficiency of WOES (LT=10%, HT=80% and $c = 1.5$) reaches to more than 0.757 GB/J, which is at least 66.8% higher than that of NES and OES.

## 6 Conclusion

In this paper, we have addressed the potential opportunity for green FiWi network and proposed the WOES scheme for integrating wireless and optical energy savings. Generally, the WOES scheme consists of two inactive modules EEOM and EATC. EEOM aims at the energy savings in optical back-end by using a pair of thresholds to maintain the states of ONUs, i.e., sleep or active. EATC aims at the energy savings in wireless front-end by putting idle RIs into standby state and reconfiguring the wireless topology. Through extensive simulation, we have demonstrated that WOES can significantly reduce the energy consumption of FiWi and outperforms much the traditional schemes concerning only optical energy savings. More importantly, WOES suffers from just a little performance degradation in network throughput and end-to-end delay. Therefore, the proposed WOES scheme can utilize the energy more efficiently and raises the prospect of integrating wireless and optical energy savings for green FiWi network in near future. It may be noted that, in this paper, we deal with the energy savings in wireless front-end and optical back-end. As another alternative solution, joint wireless and optical energy savings will contribute to better performance. However, this also involves the intractable joint optimization problem. In our future works, we will put more effort on the issue of joint wireless and optical energy savings.

**Acknowledgements**

This work was supported in part by the National Natural Science Foundation of China (Grant Nos. 61172051, 61071124), the Fok Ying Tung Education Foundation (Grant No. 121065), the Program for New Century Excellent Talents in University (Grant Nos. 11-0075, 12-0102), the Fundamental Research Funds for the Central Universities (Grant Nos. N110604008, N110204001), and the Specialized Research Fund for the Doctoral Program of Higher Education (Grant Nos. 20110042110023, 20110042120035, 20120042120049).

### References

1 Valcarenghi L, van D P, Raponi P G, et al. Energy efficiency in passive optical networks: where, when, and how. IEEE Netw, 2012, 26: 61–68

2 Schutz G, Correia N. Design of QoS-aware energy-efficient fiber-wireless access networks. IEEE/OSA J Optical Commun Netw, 2012, 4: 586–594

3 Du S, Zhang S, Peng Y, et al. Power-efficient RWA in dynamic WDM optical networks considering different connection holding times. Sci China Inf Sci, 2013, 56: 042306

4 Huang S, Li B, Guo B, et al. Distributed protocol for removal of loop backs with asymmetric digraph using GMPLS in p-cycle based optical networks. IEEE Trans Commun, 2011, 59: 541–551

5 Jiang D, Hu G. GARCH model-based large-scale IP traffic matrix estimation. IEEE Commun Lett, 2009, 13: 52–54

6 Zhang Z, Jiang W, Zhou H, et al. High accuracy frequency offset correction with adjustable acquisition range in OFDM systems. IEEE Trans Wirel Commun, 2005, 4: 228–237

7 Reaz A, Ramamurthi V, Tornatore M, et al. Cost-efficient design for higher capacity hybrid wireless-optical broadband access network (WOBAN). Comput Netw, 2011, 55: 2138–2149

8 Reaz A, Ramamurthi V, Sarkar S, et al. CaDAR: an efficient routing algorithm for a wireless-optical broadband access network (WOBAN). IEEE/OSA J Opt Commun Netw, 2009, 1: 392–403

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7

9 Sarkar S, Dixit S, Mukherjee B. Hybrid wireless-optical broadband-access network(WOBAN): a review of relevant challenges. IEEE/ACM Trans Netw, 2007, 25: 3329–3339

10 Lee K, Sedighi B, Tucker R S. Energy efficiency of optical transceivers in fiber access networks. IEEE/OSA J Opt Commun Netw, 2012, 4: A59–A68

11 Sankaran G C, Sivalingam K M. ONU buffer elimination for power savings in passive optical networks. In: Proceedings of IEEE International Conference on Communications, Kyoto, 2011. 1–5

12 Yan Y, Wong S, Valcarenghi L, et al. Energy management mechanism for ethernet passive optical networks (EPONs), In: Proceedings of IEEE International Conference on Communications, Cape Town, 2010. 1–5

13 Shi L, Mukherjee B, Lee S S. Energy-efficient PON with sleep-mode ONU: progress, challenges, and solutions. IEEE Netw, 2012, 26: 36–41

14 Zhang J, Ansari N. Toward energy-efficient and 10G-EPON with sleep-aware 1G-EPON MAC control and scheduling. IEEE Commun Mag, 2011, 49: s33–s38

15 Chowdhury P, Tornatore M, Sarkar S, et al. Building a green wireless-optical broadband access network (WOBAN). IEEE/OSA J Lightwave Technol, 2010, 28: 2219–2229

16 Kantarci B, Mouftah H T. Energy efficiency in the extended-reach fiber-wireless access networks. IEEE Network, 2012, 6: 28–35

17 Liu X, Ghazisaidi N, Ivanescu L, et al. On the tradeoff between energy saving and QoS support for video delivery in EEE-based FiWi networks using real-world traffic traces. IEEE/OSA J Lightwave Technol, 2011, 29: 2670–2676

18 Kazovsky L G, Ayhan T, Ribeiro M R N, et al. Energy efficient optical-wireless residential access/in-house networks. In: Proceedings of International Conference on Transparent Optical Networks (ICTON), Stockholm, 2011. 1–4

19 Chieochan S, Hossain E. Channel assignment for throughput optimization in multichannel multiradio wireless mesh networks using network coding. IEEE Trans Mobile Comput, 2013, 12: 118–135

20 Zhang Z, Long K, Zhao M, et al. Joint frame synchronization and frequency offset estimation in OFDM systems. IEEE Trans Broadcast, 2005, 51: 389–394

21 Lin T, Hsieh K, Huang H. Applying genetic algorithms for multiradio wireless mesh network planning. IEEE Trans Veh Technol, 2012, 61: 2256–2270

22 Huang S, Lian W, Zhang X, et al. A novel method to evaluate clustering algorithms for hierarchical optical networks. Photonic Netw Commun, 2012, 23: 183–190

23 Monoyios D, Vlachos K. Multiobjective genetic algorithms for solving the impairment-aware routing and wavelength assignment problem. IEEE/OSA J Opt Commun Netw, 2011, 3: 40–47

24 Liu T, Liao W. Interplay of network topology and channel assignment in multi-radio multi-rate multi-channel wireless mesh networks. In: Proceedings of IEEE Global Telecommunications Conference, New Orleans, 2008. 1–5

https://engine.scichina.com/doi/10.1007/s11432-013-4958-7