A Load Adaptive and Fault Tolerant Framework for Energy Saving in Fiber-Wireless Access Networks

A. Barradas, N. Correia, J. Coimbra and G. Schütz

***Abstract*—Energy saving in telecommunication networks is an important criterion when planning access networks. In fiber-wireless access networks the energy saving potential is high, when compared with other architectures, because different routes and optical access points can be used by routers at the wireless section. Although some proposals to increase energy efficiency in these architectures have been presented, these are not approaches that can adapt to variations in traffic load or distribution of traffic across the network. Here we fill such gap and propose a load adaptive and fault tolerant framework for energy saving in fiber-wireless access networks. This framework allows ONUs to enter in long standing sleep mode under low traffic conditions, reducing energy waste, permiting fast reaction to ONU/fiber failures, and QoS to be kept at a certain level. Results show that significant energy savings can be achieved under low to medium traffic loads while keeping QoS and fault tolerance.**

***Index Terms*—Energy saving, fiber-wireless, load adaptive, QoS, fault tolerance.**

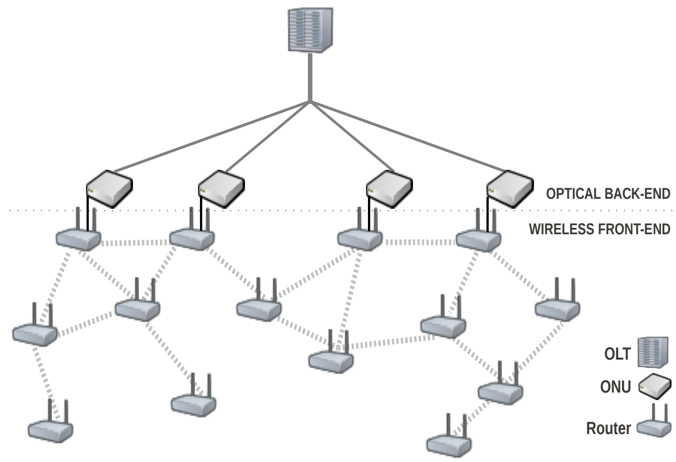

Fig. 1. Fiber-wireless access network architecture.

I. INTRODUCTION

The huge growth of broadband access network subscribers and high bandwidth consumption by applications and services led to growing problems arising from congestion at the network edge. To cope with such bandwidth needs, fiber has been deployed closer to the end user. However, despite its huge bandwidth and reliability, fiber lacks ubiquity. This fact has leveraged the emergence of hybrid fiber-wireless (FiWi) access networks, where an optical back-end and a wireless front-end are combined [1]. This paradigm is able to provide high throughput and ubiquity in a cost-effective way [2].

In wireless networks the throughput and availability can be improved, in a cost-effective manner, if routers have multiple radio interfaces allowing multi-channel communication [3], [4]. For example, current IEEE 802.11b/g and 802.11a standards provide 3 and 12 orthogonal channels, respectively, that can work simultaneously with negligible inter-channel interference [5]. In single-radio architectures, an increase in the number of wireless routers leads to more hops, decreasing the throughput and degrading the performance of the network. When multiple radios are used such performance degradation can be avoided [6]. In this article it is assumed that wireless front-end routers have multiple radios.

More recently, energy saving in telecommunication networks became a quite important research topic [7]. Research conducted in this area has shown that the access network section is the part of telecommunication networks where there is more energy consumption [8], [9]. Energy efficiency becomes, therefore, a very important criterion when planning access networks. In the context of FiWi access networks, the potential for energy saving increases since wireless and wired technologies are linked. This is so because the main purpose of optical network units (ONUs), at the optical back-end, is to provide Internet access to users connected to wireless routers, and different routes and optical access points can be used by front-end wireless nodes. This is illustrated in Figure 1 where it can be seen that wireless routers can forward their packets toward different ONUs. This flexibility enables the use of frequency assignment and routing policies at the wireless front-end, that promote long standing sleep of ONUs placed near areas with low traffic intensity, over some period in time, as long as an alternative route toward an active ONU exists.

In networks where traffic load significantly changes over time, load adaptive energy saving schemes should be adopted for network resources to be activated/deactivated according to network load conditions, allowing energy consumption to be reduced. These schemes should not be prone to instabilities in the IP routing, should not decrease network fault tolerance and should keep QoS conditions provided to users. In this article a load adaptive and fault tolerant framework for energy saving in FiWi networks is proposed. According to current network load, this framework allows:

- some ONUs to enter in long standing sleep mode, reducing energy waste;
- fast reaction to ONU/fiber failures, while keeping energy saving, thus providing a fault tolerant network;
- QoS sustained at a certain level, by spreading the traffic, limiting number of hops, and waking up ONUs if necessary;
- IP routing service to operate normally with no instabil-

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A. Barradas, N. Correia, J. Coimbra, and G. Schütz are with the Center for Electronic, Optoelectronic and Telecommunications (CEOT), University of Algarve, Faculty of Science and Technology, 8005-139 Faro, Portugal (emails: {abarra,ncorreia,jcoimbra,gschutz}@ualg.pt).

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ities;

All these issues will be highlighted and explained throughout the article, which is organized as follows. Section II discusses FiWi access architectures, their energy saving potential and signaling used in the implementation of energy saving schemes. In Section III the energy saving problem under discussion is introduced together with the proposed approach to solve it. Sections IV and V goes into the details of the energy saving framework proposed, formalizing the initial planning procedure and dynamically operating procedures, respectively. In Section VI the results are analysed, while Section VII concludes the article.

II. Fiber-Wireless Access Networks

A. Network Architecture

FiWi access networks include two sections termed back-end and front-end, as illustrated in Figure 1. The back-end includes an optical access network, where optical links are brought from the central office (CO) toward some place near the end users. The dominant technology at this optical section is the passive optical network (PON) including optical line terminals (OLTs), located at the CO, and optical network units (ONUs) providing a wired connection to wireless gateway routers. At the front-end a multi-hop wireless mesh network provides user connectivity. At this front-end section, any radio frequency technology can be used, such as 802.11 or WiMAX. Gateways/ONUs can be strategically placed to better serve the wireless community [2]. These FiWi architectures are intended for outdoor deployment and not for indoor as wireless connections between wireless routers placed at different rooms may fail.

In traditional time-division multiplexed (TDM) PONs two wavelength channels are used, one for upstream and the other for downstream. For upstream the ONUs must contend for bandwidth, through the exchange of grant request/response messages with the OLT, while downstream traffic is broadcast to all the ONUs. An ONU discards any traffic not destined to it.

B. Energy Efficiency

In the context of FiWi access networks, although PONs consume less power when compared with other access technologies, further power consumption decrease is possible if sleep mode of devices is explored [10]. Within PONs, the ONUs are the devices where a reduction in energy expenditure would have more impact on network energy efficiency [11], [12]. This is so because, when compared with the OLTs for example, ONUs are higher in number and aggregate less traffic. Besides this, the downstream traffic of current PONs is broadcast to all ONUs even though some ONUs have not requested it. The ONU simply discards data not destined to it, meaning that energy waste exists. This could be avoided if ONUs switch to sleep mode when there is no traffic to send/receive. During sleep periods, any data arriving to the OLT, and destined to a sleeping ONU, must be buffered. The same happens for upstream traffic flow.

ONU sleep mode types include: *i*) deep sleep; *ii*) fast/cyclic sleep [9]. When in deep sleep mode most ONU functionalities, including transmitter and receiver, are turned off. The ONU will wake up when the customer switches it on or when a local timer expires, meaning that deep sleep can

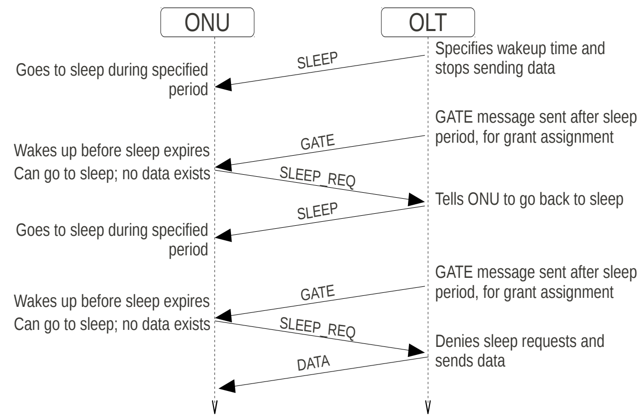

Fig. 2. OLT-initiated sleep mode signaling.

be used only when service loss is tolerable. This solution allows maximal power saving. On the contrary, fast/cyclic sleep mode allows the ONU to alternate between sleep and awake periods, which can be initiated/terminated by either the OLT or the ONU. An OLT-initiated scenario is illustrated in Figure 2 [10]. The OLT first instructs the ONU to go to sleep. After the sleep period finishes, the OLT sends a downstream grant through a GATE message. If the ONU has no traffic to send, a SLEEP_REQ message is sent. The OLT may accept or deny a sleep request from the ONU depending on the existence of traffic waiting to be sent from the OLT toward the ONU. This timing diagram illustrates an OLT-initiated scenario with successful message exchange, but other scenarios are possible. See [10], [13] for more details.

The performance of the fast/cyclic sleep scheme depends on the sleep mode scheduling and on the dynamic bandwidth allocation (DBA). The approach proposed here intends to increase the energy efficiency in FiWi networks by allowing long standing sleep periods at ONUs where low traffic activity was detected, as long as an alternative awake ONU can be used without deteriorating QoS, increasing the performance of fast/cyclic sleep scheme.

C. State of the Art

Many approaches have been proposed for ONUs to enter sleep mode. In [8] instead of keeping the ONU awake, because the OLT is not able to determine the next wakeup time, the OLT assigns first a minimum value of sleep window to the ONU. This sleep window then grows while no traffic arrives to the ONU. In [14] the use of a slotted fixed bandwidth allocation (FBA) scheme is proposed when the system is operating at low load, not considering QoS constraints. Approaches depending on traffic behaviour have been proposed in [15], [16]. The authors in [15] propose a method based on inter-arrival time between frames to determine the length of sleep periods. In [16] a scheme that tries to match downstream transmission with upstream time slots assigned to the ONUs is proposed. All these schemes are fast/cyclic sleep schemes applied to PONs and not FiWi.

Proposals to improve energy efficiency in FiWi networks are still scarce. In [17] a QoS aware energy efficient routing algorithm is proposed that tries to minimize the number of awake ONUs and is not dynamic. The approach in [18] maximizes the number of sleeping ONUs, forcing traffic to be rerouted toward the set of awake ONUs. We believe that the approach in [18] is more suitable for single channel scenarios, while our approach can be used in single and multi-channel scenarios while providing fault-tolerance. If wireless radios are tuned to different channels, to improve throughput, the failure of an ONU could leave some nodes with no route toward another ONU. Our approach is prepared for these scenarios. Also, our approach changes network state smoothly since a single ONU is chosen to go to sleep or wakeup, and in [18] many nodes can be put to sleep all of a sudden. We also use a moving average for traffic load monitoring at the ONUs, which avoids rushed decisions.

In [11] a mathematical formalization and an efficient algorithm to schedule sleep and awake periods at every node of the FiWi access network is developed. ONUs switch between short length awake and sleeping periods to keep packet delay acceptable. Scheduling is planned also based on a given traffic matrix, and dynamic decisions based on current traffic are not done. As far as known no dynamic load adaptive scheme to improve energy efficiency in FiWi networks has been proposed in the literature. Our approach fills this gap. The approach proposed also takes into consideration the provision of QoS and fault-tolerance.

III. Energy Saving (ES) Problem

A. Problem Definition

According to what has been previously stated about FiWi architectures, ONUs can be identified as the devices where a reduction in energy consumption would have more impact on energy expenditure. Therefore, the energy saving (ES) problem can be defined as follows, considering that the front-end can have multiple radios, meaning that nodes may operate on multiple available frequencies:

Definition 1 (ES Problem): Given a FiWi access network $\mathcal{G}(\mathcal{N},\mathcal{L})$, where $\mathcal{N}$ is the set of wireless routers and ONUs, and $\mathcal{L}$ is the set of wireless links, plan the frequency assignment for the wireless front-end and sleep mode of ONUs so that energy efficiency at the ONUs is maximized while keeping QoS acceptable when routing traffic demands.

B. ES Solving Framework

The structure of the framework proposed to solve the ES problem includes an initial procedure where wireless frequency assignment, at the front-end, and a set of sleep mode assignment scenarios for the ONUs, at the optical section, are planned. A sleep mode assignment scenario, from such set, is to be adopted according to network traffic distribution and load. Thus, sleep scenarios will serve as a basis for a set of dynamically operating procedures, also proposed and discussed in detail.

ES Initial Planning Procedure*:* Front-end frequency assignment and sleep mode assignment scenarios, being planned at this initial procedure, should be prepared for any traffic load as traffic may oscillate over time. Furthermore, since energy saving is a concern, frequency assignment should enable the largest number of ONUs to go to sleep, while ensuring the existence of routes toward the active ONUs. Therefore, since traffic should not be considered at this stage, meaning that load across the network is not known, frequency assignment should be done in such a way that every ONU is able to go to sleep, in case of light load at the ONU, thus ensuring fairness among ONUs in terms of sleeping possibility. This is done through sleep mode scenarios as it will become clear in the following section. Under this premise, the proposed approach maximizes the number of ONUs able to go to sleep in every scenario. This way, the appropriate sleep mode scenario, to be applied to the ONUs, can be adopted by dynamically operating procedures according to the network area that is more loaded at the moment.

Definition 2 (ES Initial Planning Problem): Given a FiWi access network $\mathcal{G}(\mathcal{N},\mathcal{L})$, where $\mathcal{N}$ is the set of wireless routers and ONUs, and $\mathcal{L}$ is the set of wireless links, find the frequency assignment for radios at the wireless front-end, and a set of ONU sleep mode assignment scenarios for hereafter use, so as to allow every ONU to go to sleep mode, together with as many other ONUs as possible, while ensuring the existence of a route between each wireless node and at least one active ONU.

ES Dynamically Operating Procedures*:* Sleep mode assignment to ONUs should change over time and adapt to traffic oscillations. Based on the output of the initial planning procedure, an initial sleep mode scenario can be adopted and then, according to traffic changes or network failure, procedures for the network to adapt itself should be adopted so that energy saving can be achieved, while keeping QoS acceptable when routing traffic demands between wireless nodes and active ONUs. As it will become clear in Section V, besides a *Setup* procedure where the initially adopted sleep mode scenario is defined, three dynamically operating procedures are proposed: *GoToSleep*, *WakeUp* and *ReactToFailure*.

IV. ES Initial Planning Procedure Formalization

A. Assumptions and Notation

In the following formalization, the FiWi network is represented by a directed graph $\mathcal{G}(\mathcal{N},\mathcal{L})$, where $\mathcal{N}$ includes the set of wireless devices and the set of ONUs, denoted by $\mathcal{W}$ and $\mathcal{O}$, respectively, and $\mathcal{L}$ includes wireless links available at the front-end. Directed routes, from wireless routers toward ONUs, will be chosen while deciding for the best frequency assignment, to ensure connectivity between front and back ends. However, after finding the optimal frequency assignment, and fixing channels used by radios, any route at the wireless front-end can be used for upstream and downstream transmission.

Let us define $\mathcal{M} = \{1, 2, ..., |\mathcal{O}|\}$ as the set of sleep mode scenarios that must be considered. A scenario m included in $\mathcal{M}$ basically forces ONU m to be in sleep mode, while the mode of the other ONUs is not constraint[1]. The set of available channels, to any wireless device, is denoted by $\mathcal{C}$ and the total number of radios available at the network is denoted by R. The average number of hops taken by packets can not exceed H, while the total number of route hops

[1]The mode (sleep or awake) of these ONUs will be determined when finding the solution for the initial planning procedure of the ES problem.

at any set of interfering wireless links, thereby requiring TDM, cannot exceed F. The interference model adopted is explained in Section IV-C. QoS can be ensured through these two parameters, H and F, as explained in the following section. The variables are the following:

- λ^{MAX} Maximum number of ONUs that can simultaneously switch to sleep mode;
- $\alpha_{o,m}$ One if ONU $o \in \mathcal{O}$ is in sleep mode under scenario $m \in \mathcal{M}$;
- $\delta^{l,c}_{w,m}$ One if the route of wireless router $w \in \mathcal{W}$, toward an active ONU in scenario $m \in \mathcal{M}$, is using link $l \in \mathcal{L}$ on channel $c \in \mathcal{C}$.
- $\rho_{n,c}$ One if node $n \in \mathcal{N}$ (wireless router or gateway attached to ONU) operates on channel $c \in \mathcal{C}$.

B. Mathematical Formalization

$$\text{Maximize } \lambda^{MAX} \quad (1)$$

– Lower bound on the number of sleeping ONUs:

$$\sum_{o\in\mathcal{O}} \alpha_{o,m} \geq \lambda^{MAX},\ \forall m \in \mathcal{M} \quad (2)$$

This is done in a per sleep mode scenario basis in order to ensure that every ONU is able to go to sleep (fairness).

– Route flow conservation:

$$\sum_{l\in\mathcal{L}:s(l)=w} \sum_{c\in\mathcal{C}} \delta^{l,c}_{w,m} = 1,\ \forall w \in \mathcal{W}, \forall m \in \mathcal{M} \quad (3)$$

$$\sum_{l\in\mathcal{L}:d(l)\in\mathcal{O}} \sum_{c\in\mathcal{C}} \delta^{l,c}_{w,m} = 1,\ \forall w \in \mathcal{W}, \forall m \in \mathcal{M} \quad (4)$$

$$\sum_{l\in\mathcal{L}:s(l)=w'} \sum_{c\in\mathcal{C}} \delta^{l,c}_{w,m} - \sum_{l\in\mathcal{L}:d(l)=w'} \sum_{c\in\mathcal{C}} \delta^{l,c}_{w,m} = 0, \\ ,\forall w, w' \in \mathcal{W} : w' \neq w, \forall m \in \mathcal{M} \quad (5)$$

such that $s(l)$ and $d(l)$ denote the source and destination nodes of link $l \in \mathcal{L}$. These ensure that wireless nodes have a route toward an ONU under any sleep mode scenario.

– Avoiding the use of sleeping ONUs:

$$\sum_{w\in\mathcal{W}} \sum_{l\in\mathcal{L}:d(l)=o} \sum_{c\in\mathcal{C}} \delta^{l,c}_{w,m} \leq (1-\alpha_{o,m}) \times |\mathcal{W}|,\ \forall o \in \mathcal{O},\ \forall m \in \mathcal{M} \quad (6)$$

$$\alpha_{o,m} \geq l_{o,m},\ \forall o \in \mathcal{O}, \forall m \in \mathcal{M} \quad (7)$$

where $l_{o,m}$, given as input, is 1 if ONU o is forced to be in sleep mode when in scenario $m \in \mathcal{M}$[2].

– Radio channel assignment

$$\rho_{n,c} \geq \frac{\sum_{w\in\mathcal{W}} \sum_{l\in\mathcal{L}:s(l)=n} \delta^{l,c}_{w,m} + \sum_{w\in\mathcal{W}} \sum_{l\in\mathcal{L}:d(l)=n} \delta^{l,c}_{w,m}}{|\mathcal{L}|}, \\ ,\forall n \in \mathcal{N}, \forall c \in \mathcal{C} \quad (8)$$

$$\sum_{n\in\mathcal{N}} \sum_{c\in\mathcal{C}} \rho_{n,c} \leq R, \forall n \in \mathcal{N} \quad (9)$$

Expression (8) ensures that a channel, at some node, is assigned to a radio if a route requires it. Expression (9) ensures that the total number of radios does not exceed R, the available radios.

– QoS guarantees:

$$\frac{\sum_{w\in\mathcal{W}} \sum_{l\in\mathcal{L}} \sum_{c\in\mathcal{C}} \delta^{l,c}_{w,m}}{|\mathcal{W}|} \leq H,\ \forall m \in \mathcal{M} \quad (10)$$

$$\sum_{w\in\mathcal{W}} \sum_{l'\in\mathcal{L}:I(l,l')=1} \delta^{l',c}_{w,m} \leq F,\ \forall l \in \mathcal{L}, \forall c \in \mathcal{C}, \forall m \in \mathcal{M} \quad (11)$$

These two expressions impose an upper bound on the average number of hops taken by packets, and an upper bound on the usage of any set of interfering wireless links, by routes being built. The latest is used to encourage the use of different channels at interfering areas having more routes passing through it. A tight bound for the number of hops will be around $H = max_{i\in\mathcal{W}}\{H_{i2}\}$, where H_{ik} is the number of hops of the k^{th} shortest path starting at $i \in \mathcal{W}$ and ending at the optical section (any ONU), considering the feasible wireless links[3] at the wireless section. This is so because H_{i1} may not be admissible under some sleep mode scenario (if the shortest path is toward an ONU that is forced to be in sleep mode). Expression (11), which encourages the use of different channels, must take into consideration interference among links. This information can be extracted from the wireless front-end graph: $I(l,l') = 1$ indicates that link l' is at the interference range of l, not allowing simultaneous transmission if using the same channel. The value of F can be defined around $\frac{Average\ Number\ of\ Interfering\ Links}{|\mathcal{C}|}$ but, according to the network topology and position of gateways, tighter values may become possible. The assumed interference model is defined in the following section.

– Binary and Integer Variables:

$$\alpha_{o,m}, \delta^{l,c}_{w,m}, \rho_{n,c} \in \{0,1\}; \lambda^{MAX} \in \mathbb{N} \quad (12)$$

C. Interference Model

At the wireless front-end, it is assumed that any two interfaces operating at the same channel, and at the transmission range of each other, will have an established wireless link that can be used for transmission and reception using time division. While the transmission range of a radio defines the maximum physical range of the radio signal, the interference range determines the area in which other nodes will not be able to receive or transmit signals successfully, if using the same channel. Considering a specific directed link l, it is assumed that any other link l' can interfere with l, unable to transmit on the same channel simultaneously, if and only if $x = s(l')$ or $y = d(l')$ is at the interference range of $u = s(l)$ or $v = d(l)$ i.e.,

$$d_{u,x} < (1+\kappa)T_u \text{ or } d_{u,y} < (1+\kappa)T_u \\ \text{or } d_{v,x} < (1+\kappa)T_v \text{ or } d_{v,y} < (1+\kappa)T_v \quad (13)$$

where $d_{u,x}$ is the distance between u and x, T_u and T_v are the transmission ranges of radios u and v, respectively, and $\kappa \geq 0$ is the increase of the interference range over the transmission range. For simplicity it is assumed $\kappa = 0$.

[2]Please note that although $\alpha_{m,m} = 1$ could be used in this particular case, the goal is to keep this constraint applicable to other scenarios (e.g. ONUs not allowed to go to sleep mode, or some ONUs forced to be in sleep mode)

[3]A feasible wireless link between a and b exists if a and b are at the transmission range of each other. That is, no channel assignment is assumed yet.

V. ES Dynamically Operating Procedures Details

The previous mathematical formalization, besides planning wireless frequency, provides the available set of sleep mode assignment scenarios. We now propose a set of dynamically operating procedures that can be used during network operation, which take into consideration the scenarios that can be adopted.

A. Initial Setup

Let us assume that $h_{w,o}$ denotes the number of hops from $w \in \mathcal{W}$ toward $o \in \mathcal{O}$ following the shortest path, which does not change since the frequency assignment at the front-end has been previously computed by formalization of Section IV and is given as input, and that $\Delta_o = \{w \in \mathcal{W} : h_{w,o} = min_{o' \in \mathcal{O}^W}(h_{w,o'})\}$ defines a set that includes all wireless nodes whose shortest path is toward ONU $o \in \mathcal{O}^W$, where $\mathcal{O}^W \subset \mathcal{O}$ is the set of currently awake ONUs. That is, according to current active and asleep ONUs, the ONU o is the best choice in terms of hops. Note that $h_{w,o}$ is based on the frequencies assigned to radios and no link weights or loads are considered. This is known information, requiring no link advertisements.

The solution obtained by formalization of Section IV provides the set of active and asleep ONUs for each scenario $m \in \mathcal{M}$. These sets will be first examined by an initial setup procedure in order to pick the scenario that will, most probably, lead to a less congested network. The congestion impact is defined as

$$Impact(m) = \sum_{o \in \mathcal{O}:\alpha_{o,m}=1} \frac{\sum_{w \in \Delta_o} min_{o' \in \mathcal{O}:\alpha_{o',m}=0}\{h_{w,o'}\}}{|\Delta_o|}, \quad \forall m \in \mathcal{M}, \quad (14)$$

where $\alpha_{o,m}$ is extracted from the space of solutions, and $\mathcal{O}^W = \mathcal{O}$ is assumed for Δ_o computation. The initial state of the ONUs, awake or sleeping, will then be set according to the scenario having the smallest congestion impact. The fraction included in the expression basically gives the impact, in terms of average number of hops, of putting an ONU into sleep mode. The whole expression gives the network impact associated with a sleep mode scenario, which may involve many ONUs in sleep mode.

As previously stated, the best scenario in terms of congestion impact, which can be found using expression (14), determines the initial state of the ONUs. From now on, $\mathcal{O}^{AW}$ is used to denote the initial set of awake ONUs, which are not allowed to go to sleep mode since they ensure the existence of a route from any wireless node toward the optical section[4], as defined in formalization of Section IV. As time runs, ONUs may wakeup or go to sleep dynamically, according to network conditions. The set of current awake ONUs, at some instance in time, will be denoted by $\mathcal{O}^W$, as already stated. Therefore, set $\mathcal{O}^{AW}$ will always be part of $\mathcal{O}^W$, the set of awake ONUs that changes dynamically over time, and initially $\mathcal{O}^W = \mathcal{O}^{AW}$. As time evolves Δ_o will dynamically change to accommodate current sleep/awake mode of the ONUs.

The sleep/awake mode of ONUs must adapt to network traffic conditions. For this purpose, it is assumed that the number of packets/frames waiting at incoming and outgoing queues is recorded periodically (e.g once per second), at the OLT, using a exponential weighted moving average. More specifically, the traffic intensity of ONU $o \in \mathcal{O}$, denoted by t_o, which will be taken into consideration when deciding for sleep/awake modes, will be

$$t_o = (1-\beta) \times t_o + \beta \times t_o^{Sample}, \quad (15)$$

where t_o^{Sample} is the current number of packets/frames waiting at incoming and outgoing queues and $0 \leq \beta \leq 1$. As t_o^{Sample} can vary significantly under bursty traffic conditions, applying such moving average helps t_o to change smoothly, avoiding rushed decisions regarding switching the mode of an ONU. Initially t_o is set to $[\frac{(Th^{max}-Th^{min})}{2}] + Th^{min}$, $\forall o \in \mathcal{O}$, as no network traffic behaviour is known yet. The Th^{min} and Th^{max} are minimum and maximum packet/frame number thresholds, respectively, used to evaluate when to put an ONU to sleep or wakeup an ONU that is sleeping, and are used in the procedures discussed in the following sections. As time runs and t_o values are updated using expression (15), which is done periodically, t_o will approximate real network traffic conditions. Such initialization of t_o, and the use of thresholds, avoids ONU oscillations from sleep to awake mode, or vice versa. The value to be assigned to Th^{min} and Th^{max}, in a real implementation, will depend on traffic burstiness and network connectivity degrees. These two issues basically determine the impact of rerouting a certain amount of traffic.

To evaluate the average network load associated with ONU $o \in \mathcal{O}$, the following load function will be used

$$Load(o) = \frac{\sum_{w \in \Delta_o} h_{w,o}}{|\Delta_o|} \times t_o. \quad (16)$$

This will be used in the procedures discussed next. In summary, the initial setup procedure would be the following:

Setup:

Step 1 - Define the set of always awake ONUs, $\mathcal{O}^{AW}$, which can be extracted from the sleep mode scenario that has the smallest impact value:

$$m^* = argmin_{m \in \mathcal{M}}\{Impact(m)\} \quad (17)$$

$$\mathcal{O}^{AW} = \{o \in \mathcal{O} : \alpha_{o,m^*} = 0\} \quad (18)$$

Step 2 - Redefine Δ_o, $\forall o \in \mathcal{O}$, according to the smallest impact scenario:

$$\Delta_o = \{w \in \mathcal{W} : h_{w,o} = min_{o' \in \mathcal{O}^{AW}}\{h_{w,o'}\}\}, \forall o \in \mathcal{O}^{AW} \quad (19)$$

$$\Delta_o = \{\}, \forall o \notin \mathcal{O}^{AW} \quad (20)$$

Step 3 - Initialize $\mathcal{O}^W = \mathcal{O}^{AW}$.
Step 4 - Initialize $t_o = [\frac{(Th^{max}-Th^{min})}{2}] + Th^{min}$, $\forall o \in \mathcal{O}$.

B. GoToSleep and WakeUp Procedures

For dynamic back-end sleep/awake mode assignment the following procedures are proposed. The GoToSleep incorporates a call to WakeUp procedure. These two procedures are linked this way to avoid sleep/awake oscillations at the ONUs. That is, an ONU just put into sleep mode should not

[4]Note that in a multi-frequency and multi-radio scenario some nodes may not have a route toward all the ONUs.

be awake immediately after by the WakeUp procedure. The goal of the GoToSleep procedure is to check which ONU in $\mathcal{O}^W$, with traffic activity below Th^{min}, should go to sleep, while the goal of the WakeUp procedure is to check which ONU in $\mathcal{O} \backslash \mathcal{O}^W$ should wakeup to reduce traffic at ONUs with traffic activity above Th^{max}. Therefore, a call to GoToSleep procedure will occur if, immediately after updating the t_o values, at least one t_o below threshold Th^{min} or above Th^{max} is detected.

Note that this kind of approach, where ONUs are occasionally put to sleep to save energy, and awake in case of network congestion, fits perfectly in FiWi networks since alternative routes toward the optical section exist, not compromising network connectivity. Moreover, ONUs are usually placed where needed meaning that a higher number of ONUs will be placed in areas of greater traffic intensity. Thus, whenever traffic intensity decreases, some ONUs can go to sleep while other alternative ONUs stay awake ensuring network traffic delivery.

GoToSleep:

Step 1 - Define the set of awake ONUs with traffic activity below threshold Th^{min}, which indicates that it may be advantageous to put an ONU in sleep mode:

$$\mathcal{T} = \{o \in \mathcal{O}^W \backslash \mathcal{O}^{AW} : t_o < Th^{min}\}. \tag{21}$$

Step 2 - Define the set of source wireless nodes that might change their routes, currently directed to an ONU o^S, toward another awake ONU o^W as:

$$\mathcal{A}^{o^S,o^W} = \{w \in \Delta_{o^S} : h_{w,o^W} = min_{o \in \mathcal{O}^W \backslash \{o^S\}}\{h_{w,o}\}\}, \quad , \forall o^S \in \mathcal{T},\ \forall o^W \in \mathcal{O}^W \backslash \{o^S\} \tag{22}$$

The average number of hops of these new routes is defined as:

$$h_{Avg}^{o^S,o^W} = \frac{\sum_{w \in \mathcal{A}^{o^S,o^W}} h_{w,o^W}}{|\mathcal{A}^{o^S,o^W}|},\ \forall o^S \in \mathcal{T},\ \forall o^W \in \mathcal{O}^W \backslash \{o^S\} \tag{23}$$

Step 3 - Choose the ONU that should go to sleep, o^{SLEEP}, which can be determined as follows:

for *each* $o^S \in \mathcal{T}$ *in increasing order of impact measured using* $\frac{\sum_{o^W \in \mathcal{O}^W \backslash \{o^S\}: \mathcal{A}^{o^S,o^W} \neq \{\}} h_{Avg}^{o^S,o^W}}{|o \in \mathcal{O}^W \backslash \{o^S\}: \mathcal{A}^{o^S,o^W} \neq \{\}|} \times t_{o^S} - Load(o^S)$ **do**
  $o^{SLEEP} = o^S$;
  for *each* $o^W \in \{\mathcal{O}^W \backslash \{o^S\} : \mathcal{A}^{o^S,o^W} \neq \{\}\}$ **do**
    if $Load(o^W) + h_{Avg}^{o^S,o^W} \times t_{o^S} \geq Th^{max}$ **then**
      $o^{SLEEP} = None$;
      Break;
    end
  end
  if $o^{SLEEP} \neq None$ **then**
    Break;
  end
end

Step 4 - Call WakeUp procedure.

Step 5 - Reassign routes of wireless nodes if $o^{SLEEP} \neq None$:

if $o^{SLEEP} \neq None$ **then**
  Update $\mathcal{A}^{o^{SLEEP},o^W}, \forall o^W \in \mathcal{O}^W \backslash \{o^S\}$;
  for *each* $o^W \in \mathcal{O}^W \backslash \{o^{SLEEP}\}$ **do**
    $\Delta_{o^W} \leftarrow \mathcal{A}^{o^{SLEEP},o^W}$;
  end
  $\Delta_{o^{SLEEP}} = \{\}$;
  Set $\mathcal{O}^W = \mathcal{O}^W \backslash \{o^{SLEEP}\}$ and notify ONU o^{SLEEP};
end

Step 6 - Set $t_o = [\frac{(Th^{max} - Th^{min})}{2}] + Th^{min}$, $\forall o \in \mathcal{O}^W$; $t_o = 0$ otherwise.

The call to WakeUp procedure is done after determining which ONU should be put to sleep, but prior to updates. This prevents the WakeUp procedure from waking up the ONU that was just put to sleep, avoiding sleep/awake oscillations. In Step 5, $\mathcal{A}^{o^{SLEEP},o^W}$ must be updated because $\mathcal{O}^W$ may have been changed in Step 4. Note also that Step 3 avoids overloading ONUs that might be near threshold Th^{max}, through condition $Load(o^W) + h_{Avg}^{o^S,o^W} \times t_{o^S} \geq Th^{max}$.

WakeUp:

Step 1 - Define the set of ONUs with traffic activity above threshold Th^{max}, which indicates that it may be advantageous to wake up a sleeping ONU:

$$\mathcal{T} = \{o \in \mathcal{O}^W : t_o > Th^{max}\}. \tag{24}$$

Step 2 - Define the set of source wireless nodes that might change their routes, currently directed to o^W, toward a currently sleeping ONU o^S as:

$$\mathcal{B}^{o^W,o^S} = \{w \in \Delta_{o^W} : h_{w,o^S} \leq h_{w,o^W}\},\ \forall o^W \in \mathcal{O}^W, \quad , \forall o^S \in \mathcal{O} \backslash \mathcal{O}^W \tag{25}$$

Step 3 - Choose the ONU whose wake up is more useful to ONUs in set $\mathcal{T}$, o^{WAKE}, which can be determined using:

$$o^{WAKE} = argmax_{o^S \in \mathcal{O} \backslash \mathcal{O}^W}\{\sum_{o^W \in \mathcal{T}} |\mathcal{B}^{o^W,o^S}|\} \tag{26}$$

Step 4 - Reassign routes of wireless nodes:

for *each* $o^W \in \mathcal{O}^W$ **do**
  $\Delta_{o^W} = \Delta_{o^W} \backslash \mathcal{B}^{o^W,o^{WAKE}}$;
  $\Delta_{o^{WAKE}} \leftarrow \mathcal{B}^{o^W,o^{WAKE}}$.
end

Step 5 - Set $\mathcal{O}^W \leftarrow o^{WAKE}$ and notify ONU o^{WAKE}.

With these procedures, decisions can be taken at the OLTs using t_o and $h_{w,o}$, which is network static information. Step 6 of the GoToSleep procedure resets the t_o values, $\forall o \in \mathcal{O}$, to a value between Th^{max} and Th^{min} for the IP routing service to be able to adapt to recent sleep/awake changes, also avoiding frequent oscillations between sleep and awake modes. This way, the sleep period will always compensate the energy wasted during the wakeup process.

C. Fault Tolerance

How to react to the failure of an ONU is an important issue, specially when a single ONU serves many wireless source nodes. The framework developed here allows, under single failure assumption, the implementation of a simple procedure that makes the necessary network adjustments in response to a failure. In this approach, sleep mode scenarios are considered, where a scenario $m \in \mathcal{M}$ forces ONU m to be in sleep mode while the other ONUs can be in either sleep or awake mode. For each of these scenarios the number of ONUs to go to sleep is maximized. Since for any scenario it is ensured the existence of routes from any wireless source node toward an active ONU, then the reaction to the failure of ONU $o^{FAIL} \in \mathcal{O}^W$ can be the activation of all the ONUs in $\{o \in \mathcal{O} : \alpha_{o,m} = 0, m = o^{FAIL}\}$. That is, the ONUs that ensure the existence of routes toward the optical section, when o^{FAIL} is forced to be in sleep mode, must be activated. This will only be required if $o^{FAIL} \in \mathcal{O}^{AW}$ since this set includes the ONUs that could not go to sleep. This way the continuous work of the network is ensured. The following reaction procedure to a failure is proposed:

ReactToFailure:

Step 1 - Denote failing ONU by o^{FAIL};
Step 2 - If $o^{FAIL} \in \mathcal{O}^W \backslash \mathcal{O}^{AW}$ then reassign routes of wireless nodes in $\Delta_{o^{FAIL}}$:
for *each* $w \in \Delta_{o^{FAIL}}$ **do**
Extract ONU o^W providing shortest route from:

$$o^W = argmin_{o^W \in \mathcal{O}^W \backslash \{o^{FAIL}\}} \{h_{w,o}\} \qquad (27)$$

$\Delta_{o^W} \leftarrow w;$
end
$\Delta_{o^{FAIL}} = \{\}.$

Step 3 - Otherwise, if $o^{FAIL} \in \mathcal{O}^{AW}$, define the set of ONUs to be activated due to failure as

$$\mathcal{T} = \{o \in \mathcal{O} : \alpha_{o,m} = 0, m = o^{FAIL}\} \cap \{\mathcal{O} \backslash \mathcal{O}^W\} \qquad (28)$$

and reassign routes of wireless nodes as follows:
for *each* o^{WAKE} *in* $\mathcal{T}$ **do**
Define the set of wireless nodes using $o^W \in \mathcal{O}^W$ that will benefit with the waking up of ONU $o^{WAKE} \in \mathcal{T}$ as:

$$\mathcal{A}^{o^{WAKE},o^W} = \{w \in \Delta_{o^W} : h_{w,o^{WAKE}} \leq h_{w,o^W}\} \qquad (29)$$

for *each* $o^W \in \mathcal{O}^W$ **do**
$\Delta_{o^W} = \Delta_{o^W} \backslash \mathcal{A}^{o^{WAKE},o^W};$
$\Delta_{o^{WAKE}} \leftarrow \mathcal{A}^{o^{WAKE},o^W}.$
end
end

In Step 3, $\mathcal{T}$ will include the set of ONUs that were asleep but need to be activated due to failure.

D. IP Routing Service Operation

The proposed load adaptive scheme allows the IP routing service to operate normally. The IP upstream and downstream operation could be as follows:

- In traditional TDM PONs downstream traffic is broadcast to all the ONUs and an ONU discards traffic not destined to it. Whenever an ONU is put to sleep or fails, the downstream connection to its attached gateway will be detected as inaccessible by the IP layer, a high weight associated with this connection will be propagated by routers, and routing tables will find shortest paths accordingly. Concerning the frames arriving to the OLT during this process, these can be simply discarded, leaving retransmission responsibility to upper TCP/IP layers, or a mechanism that changes destination ONU frame address to an awake ONU address, must be implemented.
- In the upstream, a connection from a gateway toward an ONU that enters into sleep mode, or fails, will also be detected as inaccessible by the IP layer. After propagating a high weight associated with this connection, wireless nodes will find shortest paths accordingly. A gateway connected to ONU o can include, in its routing table, static entries toward one of the ONUs in $\{o' \in \mathcal{O} : \alpha_{o',m} = 0, m = o\}$, one of the ONUs that ensure the existence of routes toward the optical section when o is forced to be in sleep mode. This way no packet drops would occur.

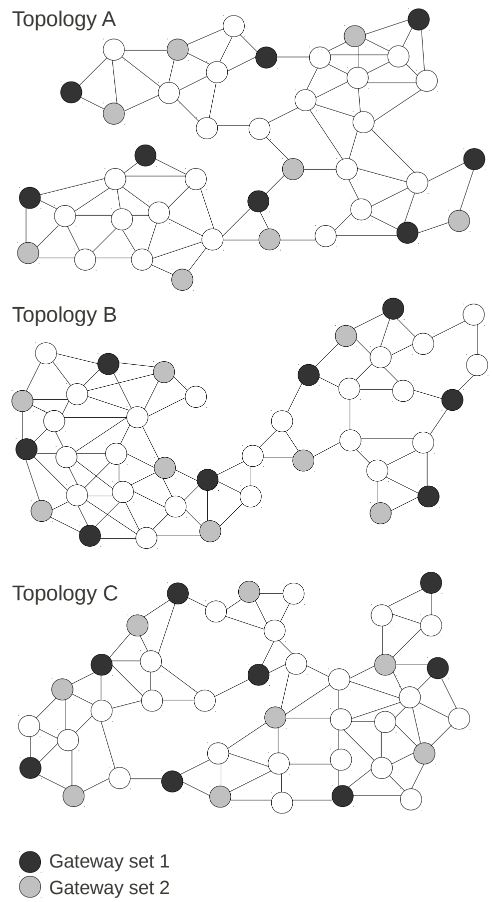

Fig. 3. Randomly generated network topologies.

VI. Analysis of Results

In this section the solutions obtained by the mathematical formalization proposed to solve the ES problem will be analysed. These were solved using the CPLEX optimization package. Tests were done for three network topologies randomly generated using the weighted proximity algorithm in [19], each having 40 wireless routers as shown in Figure 3. As for the gateways, two sets of eight nodes, randomly selected using an uniform distribution, were considered for each network. An ONU is assumed to serve one gateway.

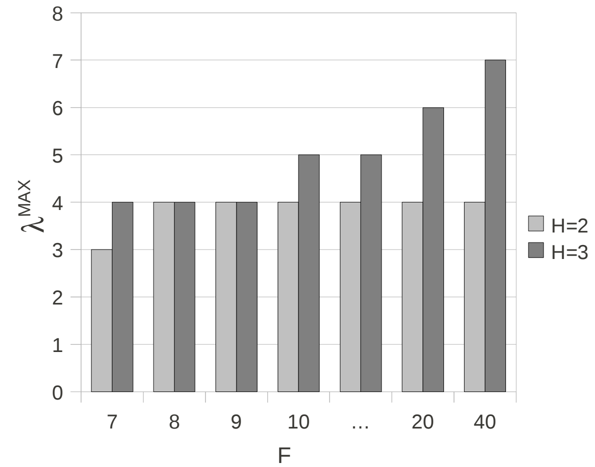

Fig. 4. ES initial planning problem results: network graph A, gateway set 1.

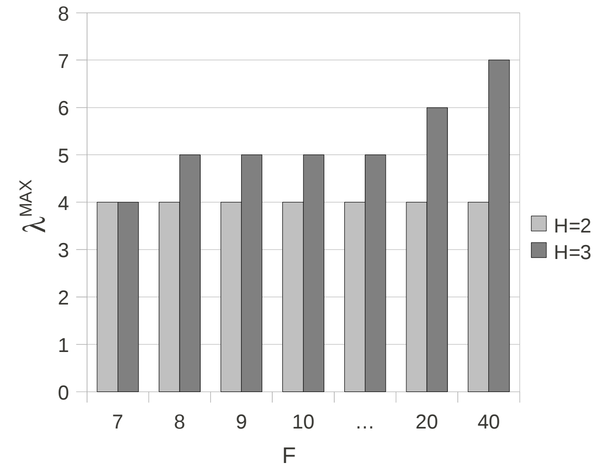

Fig. 5. ES initial planning problem results: network graph B, gateway set 1.

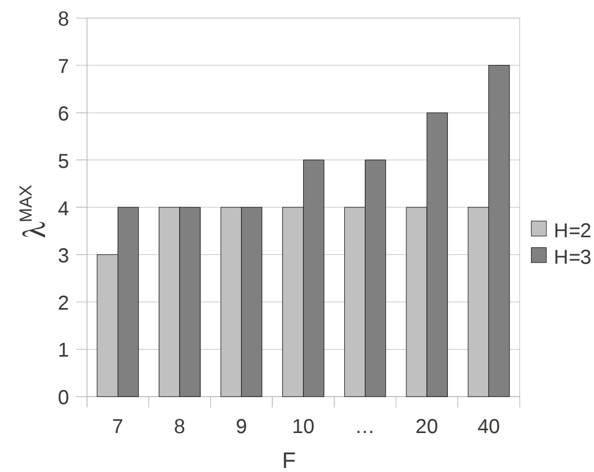

Fig. 6. ES initial planning problem results: network graph C, gateway set 1.

Results show the maximum number of ONUs that can simultaneously switch to sleep mode, λ_{MAX}. Since QoS can be ensured by parameters H and F, different values were tested for these two parameters. The results revealed that for $H \geq 3$ the value of λ_{MAX}, the maximum number of ONUs that can simultaneously switch to sleep mode, does not change considering a specific F. For $H = 1$, the problem becomes impossible to solve. This is so because each scenario m forces ONU m to be in sleep mode, while the mode of the other ONUs is to be determined by the optimizer, which means that routes must find an alternative ONU that, in some cases, requires more than a single hop. Therefore, plots in Figures 4-9 include results for $H = 2$ and $H = 3$ only. Note that H is the average number of hops, meaning that some routes can take less hops than others. In what concerns to F, which is a bound on the number of route hops at any set of interfering wireless links, solutions were found for $F \geq 7$ for almost all network topologies and gateway placements. Network topology B with gateway placement 2 is the exception and was only able to find a solution for $F \geq 10$. This is related with the gateways chosen, which increase the number of routes passing through some difficult interference area (bottleneck), when compared with other gateway placements. Note that F may include more than one hop of a particular route, as TDM is required for transmission and reception at every link in an interference area, meaning that an increase from $F \geq 7$ to $F \geq 10$, which occurred at network topology B with gateway placement 2, may be the result of a single route change or many route changes.

Even when H and F constraints are tight, 3 or 4 ONUs were able to stay simultaneously in sleep mode, while ensuring connectivity and routes between wireless routers and awake ONUs. This is so because an interference link set, at the wireless section, includes many links and, therefore, interference will always occur regardless of the ONU in this set being used. This confirms that the proposed approach fits perfectly in FiWi network. As F becomes less restrictive, the number of ONUs able to stay in sleep mode increases.

By imposing a limit on the number of route hops passing through an interference area, constraints in (11) encourage the use of different channels by radios and force the placement of radios in areas used by many routes. This means that less radios can be assigned to the other areas, having no effect on the problem solution. For the network topologies and gateway placements analysed, the R value that allowed obtaining a solution, under the F and H bound values assumed, and after which the problem solution does not improve, is 70. That is, for $R \geq 70$ the number of ONUs that can simultaneously switch to sleep mode, found by the optimizer, remains the same. Therefore, plots in Figures 4-9 would not change for $R \geq 70$. Thus, energy saving and QoS can simultaneously be provided with an average number of radios per router of $\frac{70}{|\mathcal{N}|} = \frac{70}{40} = 1.75$, where 40 is the number of wireless nodes of the topologies being analysed. No solution was obtained for $R < 70$ under the F and H bound values assumed. Solutions for $R < 70$ would require F to double or triple.

As a final conclusion we can state that, depending on the traffic load, traffic pattern and required QoS, significant energy savings can be achieved if the proposed framework is

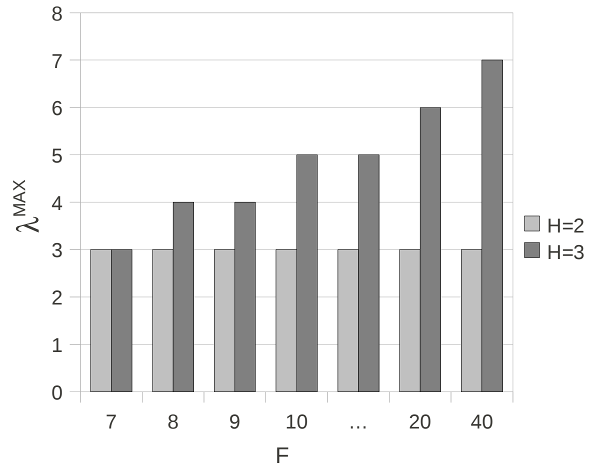

Fig. 7. ES initial planning problem results: network graph A, gateway set 2.

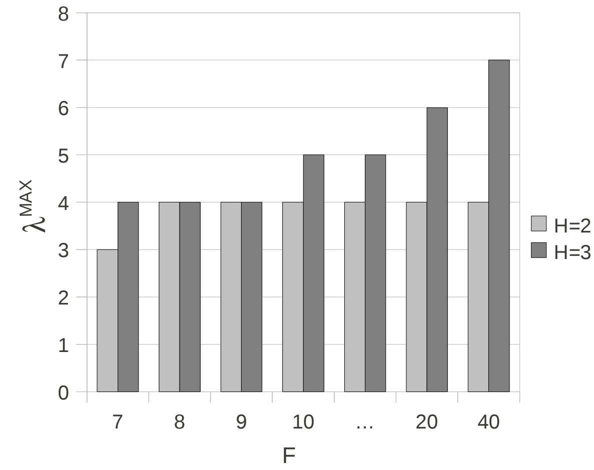

Fig. 9. ES initial planning problem results: network graph C, gateway set 2.

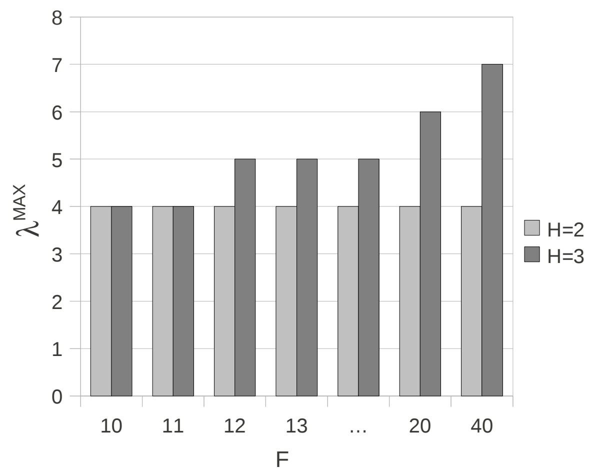

Fig. 8. ES initial planning problem results: network graph B, gateway set 2.

adopted. As an example, under light to medium traffic loads and regular traffic pattern, which prevent local power saving methods from putting ONUs into sleep mode, around 50% of energy saving can be achieved by the proposed framework since half the ONUs can be in long standing sleep mode, while providing high QoS through tight F and H parameters. This statement is true for any optical access architecture and power saving method adopted by their devices, as promoting long standing sleep through a scenario planning approach, as was done, always improves energy efficiency. Accounting the exact energy consumption reduction requires, however, going into the details of the network architecture and power saving methods, which can be left for future work as it can become itself an extensive study.

VII. Conclusions

In this article a load adaptive and fault tolerant framework for energy saving in FiWi networks has been proposed. It was demonstrated that such framework can achieve significant energy savings and procedures to implement it have been proposed. We expect that such framework can serve as a basis for energy waste reduction at FiWi access networks by network operators. Future work includes comparing the energy consumption reduction achieved when using such framework in specific optical access architectures and considering different local power saving methods adopted by devices.

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Alvaro Barradas received the four-year first degree in computer science and the Ph.D degree in electronics engineering and computing from the University of Algarve, Faro, Portugal, in 1995 and 2009 respectively. His major field of study has been on load balancing for optical networks.

Currently he is an Auxiliary Professor at the Faculty of Science and Technology from the University of Algarve, but his previous professional experience includes 2 years working on system test for computer science and telecommunications consulting companies in Lisbon and Düsseldorf. He has recently published the book with title "OBS Networks: Optimized Routes for Load Balancing and QoS Provisioning" (Germany: LAP, 2012). His current research interests include the study and simulation of hybrid networks where QoS provisioning is also challenging.

Dr. Barradas is a member of the Center of Electronics Optoelectronics and Telecommunications (CEOT) at the University of Algarve, a research center supported by the Portuguese Foundation for Science and Technology.

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Noélia Correia received her BSc (1995) and MSc (1998) in Computer Science from the University of Algarve, Faro, Portugal. The PhD (2005) in Computer Science, field of optical networks, obtained at University of Algarve, was done in collaboration with University College London, UK.

She is a lecturer at the Faculty of Science and Technology of the University of Algarve, Faro, Portugal. Her research interests include the application of optimization techniques to several network design problems, optical and access networks, and development of algorithms for networks issues.

Dr. Correia is a founding member of the Center of Electronics Optoelectronics and Telecommunications (CEOT) at the University of Algarve, a research center supported by the Portuguese Foundation for Science and Technology.

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José Coimbra received his five year BSc in Computer Science from the University of Algarve, Faro, Portugal in 2006. Afterwards, in 2008, he started to work towards his PhD, at the same university, which is to be completed in 2013. In his PhD, the allocation of resources and energy efficient routing methods are studied in the context of Fiber-Wireless Access Networks.

Since 2006, he has been a researcher at the Center of Electronics Optoelectronics and Telecommunications (CEOT), networking branch, at the University of Algarve. His major research interests include allocation of resources and routing methods on mesh dynamic networks, as well as mathematical tools such as game theory and optimization methods.

Mr. Coimbra is with the CEOT and his work is partially suported by the Foundation for Science and Technology, Portugal.

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Gabriela Schütz received her five-years graduation in Mathematics and her MSc in Statistics and Operations Research from the Faculty of Science of the University of Lisbon, Portugal, in 1985 and 1989, respectively. Her PhD in Mathematics, field of Operations Research was obtained at the University of Algarve, Portugal, in 2000.

She is a "Coordenador" Professor of Mathematics at the Electrical Engineering Department of the Institute of Engineering of the University of Algarve. Her research interests include exact methods, heuristics and evolutionary algorithms for combinatorial optimization and network design problems.

Dr. Schütz is a member of the Center of Electronics Optoelectronics and Telecommunications (CEOT) at the University of Algarve, a research center supported by the Portuguese Foundation for Science and Technology.