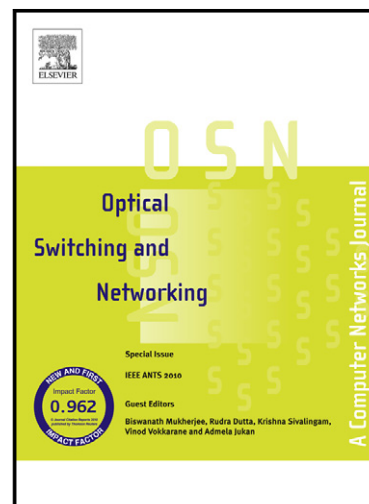


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# Cost and Energy Efficient Operation of Converged, Reconfigurable Optical Wireless Networks

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## Abstract

*This paper presents a converged fibre-to-the-home (FTTH) based access network architecture featuring wireless services. In order to fulfill the bandwidth demands from end users, a dynamic architecture is proposed with co-existence of LTE, WiMax and UWB technologies. Hybrid wavelength division multiplexing (WDM) and a time division multiplexing (TDM) based optical access network offer reconfigurable provision. This enhances the ability to allocate different wavelengths to different optical networking units (ONUs) on demand. In addition, two different channel routing modules (CRMs) are introduced in order to address the cost effectiveness and energy efficiency issues of the proposed network. Take-up rate adaptive-mode operation and traffic-adaptive power management are utilized to optimize the benefits of low investment cost with energy efficiency. Up to 26% power consumption reduction is achieved at the time of minimum traffic conditions while 10% consumption is achieved at the time of maximum traffic conditions. Besides, 23% energy saving can be achieved compared to conventional systems in fully operated stage.*

**Key Words:** *Converged optical to wireless network; dynamic bandwidth allocation; reconfigurable access networks; cost effective network; energy efficient operation*

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## 1. Introduction

Trends for evolving multimedia services over the last decade, such as high definition Internet protocol television, video on demand (VOD), etc., have driven the operators towards more bandwidth intensive network architectures [1, 2]. Not only do fixed access networks should

benefit from the network solutions, but advanced wireless networks do as well in regard to increased backhaul capacity. It is therefore a challenging research topic to design a converged fiber-wireless (FiWi) access network which delivers the emerging multimedia content and applications at much faster speeds for residential subscribers. While long term evolution (LTE) could be considered for next generation mobile telephony, wireless interoperability for microwave access (WiMax) could be designed mainly for data transmission. Besides, ultra wide band (UWB) could also be used for high definition (HD) audio and video communication applications. On the other hand, it is important concept to propose an optical access network with centralized properties in order to provide the required capacity at wireless access points. The recent survey of hybrid optical-wireless access networks explains the key underlying photonic and wireless access technologies and describes important FiWi access network architectures [3]. It is a promising solution to use combined WDM/TDM PON [4] technology as an optical back-end in consequence with wireless communication systems [5]. WDM technology can be used at the central office (CO) to transmit multiple wavelengths with appropriate modulation schemes. On the other hand, TDM can be used from the CO to the customer premises (ONUs) by featuring passive optical components at the remote nodes, such as Array Waveguide Gratings (AWGs). A WG s offer some unique properties among the other various multiplexing and routing devices, with high wavelength selectivity, low insertion loss, small size and potentially low cost. A WG s also offer spatial wavelength reuse and cyclic (self-wrapping FSR) wavelength routing, also known as Latin-routing [4]. Multi band orthogonal frequency division multiplexing (MB-OFDM) based UWB technology is a promising wireless communication solution for short ranges with variable data rates from 53 to 480 Mbps with 7.5 GHz bandwidth (3.1 – 10.6 GHz). UWB technology has a power spectral density (PSD) representative of parasitic emissions level in a typical indoor environment (FCC part 15: -41.3 dBm/MHz) [6]. Fixed WiMax, IEEE 802.16d, is a wireless access topology and it is expected to replace large wireless local area networks (LANs) in the near future [7]. In addition to WiMax, LTE v8 radio signals over fiber are also investigated. LTE v8 is mainly designed to be used in macro/microcell environments for mobile communication and it has some outstanding features such as improved system capacity with increased coverage capabilities, high peak data rates, low latency, reduced operating costs, multi-antenna support, flexible bandwidth operation and seamless integration with existing systems [8]. The transmission of OFDM-based quadruple-play services (GbE-OFDM, LTE, WiMAX and

UWB) along LR-PONs with total reach of 100 km is demonstrated without inline optical dispersion compensation in [9].

In addition to network design architecture, energy consumption and cost effectiveness could also play key role for environmental, social and political issues. Therefore, it is a challenging objective to maintain these properties with increasing traffic levels as customer numbers rise. The majority of the energy used by the Internet today is consumed in the access network, and this will continue to be the case for the near future as well. Access technologies should thus be a prime focus for energy use mitigation [10]. In order to achieve cost effectiveness, take up rates need to be considered instead of one-off investment in the initial stage [11]. The take up rate measures the percentage of eligible people who accept a particular service or benefit. In this paper, it is considered as the rate at which new broadband consumers subscribe or join the network. For instance, the average take-up rate in North America is approximately 30% over nine year construction periods, indicating the long return on investment time [12]. Next generation PONs candidates are discussed in [13] that enable short-term evolutionary and long-term revolutionary upgrades of coexistent PON infrastructures. It also reports an overview for real-time dynamic bandwidth allocation, improved privacy and guaranteed QoS, bandwidth flexibility, as well as cost-effective in-service monitoring techniques with improved resource utilization efficiency and survivability of FiWi networks. In addition, variety of advanced techniques are discussed in [14] for FiWi access networks in order to improve their reliability, availability, survivability and security with energy efficient characteristics.

In this paper, we describe converged optical and wireless access network architecture. Two different channel routing modules (CRMs) are introduced that could allow dynamic bandwidth allocation, reconfigurable assignment and service on demand converged access network characteristics. As a first objective, cost effectiveness is studied while considering take up rate adaptive mode. After, we develop the idea of traffic adaptive power management mode that leads to significant energy saving at different operational stages. Two CRMs are proposed to utilize energy efficiency and compared to a conventional system. This paper is organized as follows: Section 2 summarizes the related studies to achieve energy consumption both on PONs and FiWi networks. Section 3 introduces the proposed network architecture, while Section 4 covers the

cost effective component utilization and Section 5 analyzes the energy efficient operation. Finally, in Section 6, we summarize the key analysis results.

## 2. Related Work

There are several techniques that could be used to reduce energy consumption for PON architectures. This can be achieved either utilizing energy efficient component development [15, 16] or ONU sleep mechanism [17, 18]. Power consumption for different transceivers are studied and demonstrated, using first-order energy modeling, energy efficiency is improved [15]. 10Gbps short cavity vertical cavity surface emitting laser (10G SC-VCSEL) ONUs is proposed in [16] for WDM/TDM PON architecture to utilize improved energy-efficiency. Service level agreement (SLA) based scheduling scheme is proposed in [17] for passive optical networks. Optical line terminal can adjust the sleep time and the optical network unit can quit sleep mode for the delivery of high-priority packets. Meanwhile, there are different studies for energy-efficient WDM/TDM PON architectures with dynamic bandwidth (DBA) algorithms [18, 19]. Number of active wavelengths from the OLT is minimized by considering the network load while the energy savings at the ONUs are not implemented in [18]. On the other hand, wavelengths are activated at the OLT while considering sleep mode states of the ONUs in [19]. The implications of the main components of dynamic bandwidth allocation (DBA) algorithms in EPONs, namely grant scheduling framework, grant sizing, and grant scheduling, are discussed and examined in [20]. Sleep-aware Dynamic Bandwidth Allocation (SDBA) algorithm is introduced in [21] in order to maximize the ONU energy-saving. Algorithm is utilizing cyclic sleep mechanisms while guaranteeing QoS requirements. Particular study is experimentally validated by using an FPGA-based testbed [21]. Combine/split module (CCS) is proposed in [11] as an active remote node of an extended-reach WDM/TDM PON system to reduce initial investment and achieve good energy efficiency. The wavelengths from the OLTs are activated while considering the active subscribers with dynamic bandwidth allocation characteristics. Active remote node, that interfaces to end-users by means of the lowest cost/power consumption technology, is introduced in a recent study [22] for hybrid long-Reach fiber Access network (HYDRA) with improved cost and power consumption figures.

In addition to the energy savings in the optical back-end, it is another challenging research objective to extend the savings for the FiWi networks as well with minimal delay characteristics. In order to realize energy efficiency and improved network utilization, energy saving techniques are proposed in [23] and protocols are investigated on the performance of the proposed network over dynamic traffic profiles. A brief comparison of energy-efficient medium access control (MAC) and routing protocols are discussed in [24] for FiWi networks. On the other hand, power saving mechanisms could be used at the mobile terminals and ONUs for FiWi networks. Novel power saving mechanism is proposed in [25] for mobile terminals that controls the state of the terminals by synchronizing two power saving mechanisms for ONUs and mobile terminals. In order to resolve the additional delay problems from the power saving mechanisms, novel ONU sleep mode method is introduced in [26] which dynamically controls the ONU sleep mode while utilizing the stations energy control mechanism. To guarantee the performance of video applications in FiWi networks, issues related to the energy-efficient Quality-of-Service (QoS) support in IEEE 803.3az Energy Efficient Ethernet (EEE)-based FiWi access networks are addressed in [27]. In addition, a delay-based admission control scheme is proposed in [28] for FiWi networks that EPON is used as a backhaul in order to connect multiple WiMax base stations. The performance of the hybrid network is investigated for specific service bundles (SBs) with guaranteed quality of service (QoS) and diverse quality of service requirements. A centralized scheduling algorithm is proposed in [29] to enhance performance metrics (such as increased throughput, decreased delay, etc.) of the FiWi network. Algorithm is applied at the optical line terminal (OLT) of an EPON that resequences the in-transit packets of each flow to ensure in-order packet arrivals at the corresponding destination. Dynamic bandwidth allocation is also utilized in [29] that prioritize flows of packets to improve TCP's performance. Survivability is considered in [30] for energy efficient FiWi networks that enhances reliable and robust services under increased traffic conditions. Performance-enhancing network coding techniques are utilized and integrated in order to increase the throughput and decrease the delay of FiWi access networks for unicast and multicast traffic conditions [31]. In the recent studies, the energy efficiency of next-generation in-building IT networks is studied to deliver high-speed mobile access to end users via FiWi networks [32].

In summary, the previous works [15-22] mostly focus on the energy savings in the WDM/TDM PON architectures and [22-32] proposes energy efficient studies in the FiWi networks by combining ONU sleep mechanisms with delay control schemes. It will be promising to introduce different CRMs that could enhance reconfigurable and service on demand converged access network with cost effective and energy efficient characteristics.

### **3. Proposed Network Architecture**

The schematic diagram for the proposed converged WDM/TDM switched access network is depicted in Fig. 1. For the downstream transmission, array of (32) distributed feedback (DFB) lasers is located at the central office (CO). A laser array is used to generate the desired wavelengths and these are multiplexed onto a single waveguide by a WDM-coupler. Instead of a DFB laser array, a tunable laser can be used; however, depending on the tuning time that introduces extra latency, this might decrease downstream capacity. A CRM is proposed just before the optical splitter in order to enhance dynamic routing and reconfigurable characteristics to the network. Thirty-two wavelengths are multiplexed and transmitted from the CO, offering a unique optical path for each end user. Each remote node AWG at the DP addresses 32 end users allowing FTTH optical fiber to each premises (ONUs). User premises could be considered as a business center, shopping mall, home office etc. On the other hand, LTE or WiMax radio access network (RAN) could be configured at the ONU that would be future-proof solution to provide the highest capacity and coverage for heterogeneous networks of macro, micro and pico base stations.

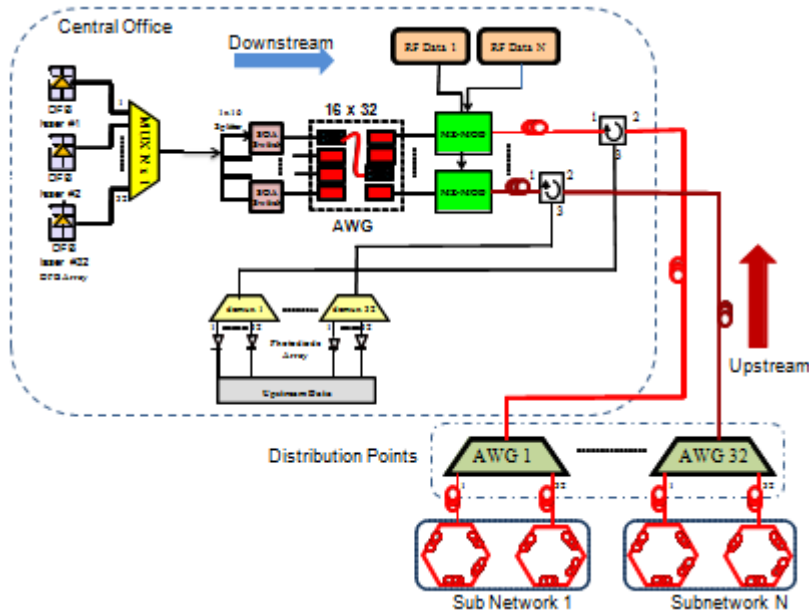


Figure 1 Block diagram of the proposed FTTH access network

Three different routing mechanisms are proposed in the paper as can be seen in Fig. 2 (a), (b) and (c) respectively. Static routing characteristics are proposed for Model 1. An erbium doped fibre amplifier (EDFA) is placed after the WDM-coupler to compensate for optical losses through the downstream direction. After that, a 1x32 optical splitter is placed in order to route to the optical signal to the input ports of the 32x32 AWG. All AWG channels are utilized for this model and all input ports of the AWG are active.

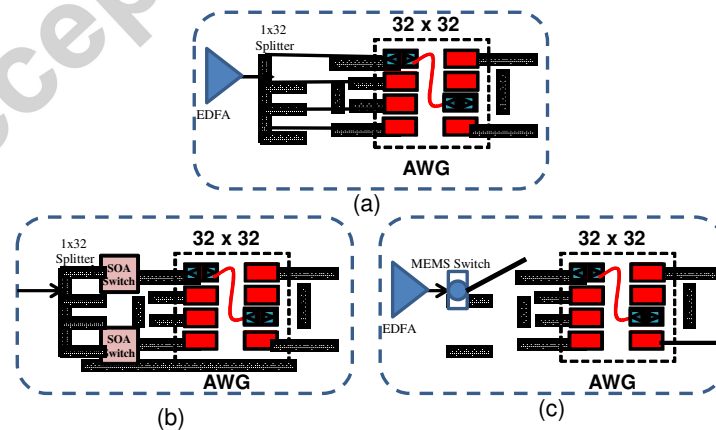


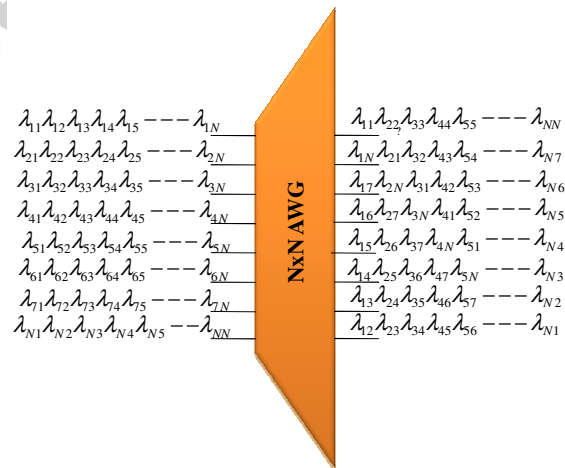
Figure 2 Different CRM modules, (a) static routing, (b) array of SOA switches and (c) MEMS switching



On the other hand, the entire beam is directed to a array of semiconductor operational amplifier (SOA) optical switches and the optical switches is used as an optical gate to the input ports of the central AWG for Model 2. The state of the SOA switches (ON/OFF) establishes the route of the input signal. SOAs can also be used to compensate the loss that arises from the optical splitter. By utilizing an appropriate optical switch duty cycle, the optical signals could be routed effectively in a WDM/TDM access network [4]. Proper matching should be obtained between the control circuit and the SOA since mismatching could cause degradation in the error vector magnitude (EVM) values at the receiver end [33]. It is also studied that the use of devices, such as SOA switches and Mach Zehnder modulator, could enhance cost efficient systems with power consumption [34, 35]. With this approach, an optical access network could offer active routing characteristics to accommodate high speed data connections especially for the mobile end users.

For Model 3, an EDFA in combination with micro electro mechanical systems (MEMS) optical switch is proposed in order to route the optical beam to the desired input ports of the 32x32 AWG.

By utilizing a passive central AWG, different wavelengths can be routed to the desired output port of the AWG while inheriting the Latin routing characteristics of the device. For instance: if the beam of light enters input port 1, and the corresponding output sequence is:  $\lambda_1, \lambda_2 \dots \lambda_n$  then if the beam enters input port 2, the output sequence will be as follows:  $\lambda_n, \lambda_1, \lambda_2 \dots \lambda_{n-1}$ . The routing characteristics of the NxN AWG is depicted in Fig. 3.



**Figure 3.** Latin routing characteristics of NxN AWG

This routing methodology can be utilized for Model 2 and 3. In addition, due to the switching characteristics of SOA and MEMS switch plus cyclic property of AWG, Model 2 and Model 3

can utilize free reconfigurable properties with active dynamic bandwidth allocation. The wavelength at the certain output port of the AWG will always be modulated by the same RF signal. To modulate a certain wavelength with the right RF signal, this wavelength has to leave the right output port of the AWG. This is the main reason to utilize optical switching equipments at the input port of the AWG, and then we can obtain the desired wavelength order at the output ports of the AWG by activating the right input port.

Each MZ-EOM generates different set of radio frequencies. Different combinations of the RF sets could be considered, such as LTE/WiMax or LTE/WiMax/UWB or WiMax only etc. Finally, the modulated wavelengths travel along single mode fibre (SMF) to the DP, where the 1x32 AWG de-multiplexes the wavelength, and routes the signal to the destination ONU. WiMax signals can be distributed in a wireless medium at the distribution points. The optical data is distributed inside the building and by using simple remote antenna units (RAUs) which are connected to each other with single mode fibers. Remote antenna units (RAUs) could be used inside user premises in order to achieve optical to electric (O/E, downstream) and electrical to optical (E/O, upstream) conversions. In addition, optical hub designs could be used to connect all the transceivers to the access network. There is a dedicated wavelength for each smart home design and the role of the hub station is to distribute the optical data to the different RAUs by means of TDM scheme. The time slots are dynamically assigned by means of demand from the several RAUs. The upstream transmission for direct modulation of WiMax signal over long haul transmission systems is discussed in the previous studies [36]. Three types of models are considered for converged optical wireless access network and all the three models will serve a maximum of 1024 ONU.

#### **4. Cost Effective Component Utilization**

##### **4.1. Required number of DFB Laser source**

In order to analyze the performances of the CRM modules, 32 DFB laser sources are activated, from a single OLT, to serve 32 TDM PONs. Therefore, the proposed system could support maximum of 1024 (32x32) residential users which offers a graceful evolution from current power-splitter-based PON infrastructures. One of the main objectives to use the CRM mechanism is to reduce power savings which are directly related to the number of reduced DFB sources and optical amplifiers. Therefore, it is crucial to analyze how the DFB number changes

with the number of subscribed ONUs. The number of DFB sources required for the initial deployment for differing numbers of subscribed customers is shown in Fig. 4. A conventional system (Model 1 - without a CRM) requires all DFB laser sources to be active from the initialization of the network. On the other hand, network scenarios with CRM modules (Model 2 and 3), new DFB sources are added to the system as soon as the existing DFBs are not sufficient to support the increasing customers. Additional DFB source is utilized if the number of users is greater than 32 with uniform probability distribution of ONUs among each DPs.

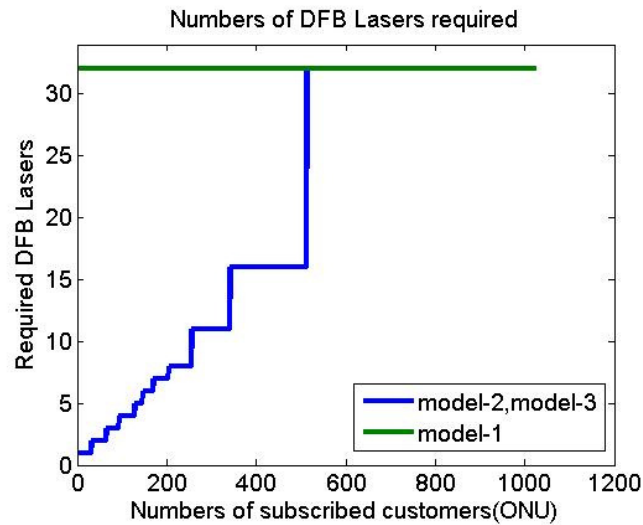


Figure 4 Number of DFB lasers versus ONU

For Model 2 and 3, the required number of DFB sources is much less than that of a conventional system for a small number of subscribed customers, starting from 1 DFB and increasing gradually to 6 DFBs when the number of subscribed customers is 200. When the number of subscribers is greater than 512, number of required DFB laser sources increases sharply from 16 to 32 because maximum DFB laser source capacity can be easily exceeded when one new laser source is connected after this subscriber number with uniform probability distribution.

CRMs for Model 2 and Model 3, SOA and MEMS switches respectively, allow Latin routing characteristics of AWG to reduce initial infrastructure cost by the invest-as-customer-approach and also reduced power consumption both in partial and full operation stage. For instance; If only 20 customers (ONU) are connected at the output port DPs, only one DFB laser diode at central office would be required that will produce one wavelength to support maximum of 32

ONU from any one of DPs. Additional DFB laser would be required only when the number of customer increases and this imply investment is not necessary unless customer is available in real scenario. In accordance, this would decrease power usage as well.

#### 4.2. Effective take up rate

Effective take-up rate measures how the network architecture utilizes system capacity for subscribed customer profiles in percentage. It can also be described as subscribed customer per system capacity [11]. 1024 customers could be supported for Model 1 (conventional system) from the initialization stage of the network. However, for Model 2 and 3, a single DFB source could be used to provide service for 32 users. As soon as the take up rate grows, more DFB lasers could be inserted to increase the system capacity. As a result, effective take up rates of Model 2 and 3 are higher than the Model 1 for the case of low take up rates. Fig. 5 illustrates the effective take up rates for the proposed models. Models with CRM modules are far above the conventional system (Model 1) for a wide range of subscriber numbers and stay above 80% for up to 300 subscribers. In addition, when the number of subscribers is less than 512, effective take-up rates are high for Model 2 and Model 3 as well. This means that the systems with CRMs have much better utilization of the system resources compared to the Model 1 which require fewer DFBs and amplifiers are to be installed with power efficient scenarios.

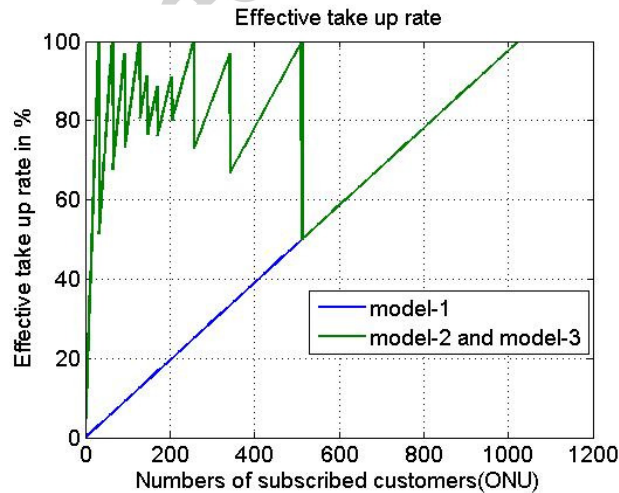


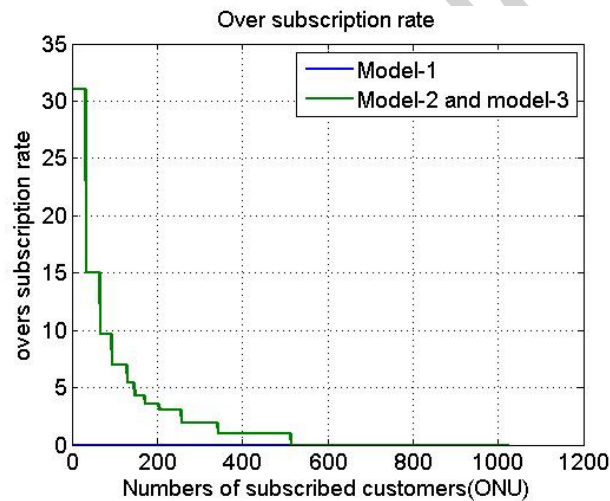
Figure 5 Effective take-up rates (%)

As soon as the number of subscribers reaches 32, there will be a need to use extra DFB laser sources which cause the effective take up rate to drop fast from 100% to a certain level. This effect can be realized from the ripples, for Model 2 and 3, in Figure 5. Effective take up rate

characteristics will increase after new subscribers connected to the system. When the total number of connected ONUs reaches to 500 and more effective take up rate will never touch 100% line as if the system capacity cannot be fully utilized any more.

### 4.3. Oversubscription rate

Oversubscription rate is another important parameter that defines the level of utilization of invested system capacity. It defines the ratio of additional connected subscribers over the total number of subscribers for which is the network designed. For instance, Model 2 and 3 are designed to give a service for 32 subscribers with a single DFB source at the initial stage. Therefore, optical amplifiers are installed to support 32 subscribers. On the other hand, 32 customers could come from any one of the 32 DPs ( $32 \times 32 = 1024$  locations). As a result, the extra number of connections is  $1024 - 32 = 992$  and the oversubscription rate is equal to  $992 / 32 = 31$ . Fig. 6 depicts the oversubscription rate versus number of subscribed customers.



**Figure 6** Oversubscription rate versus number of ONU

There is zero oversubscription for Model 1 since the system designed with the maximum capacity (1024) from the initialization stage. Oversubscription rate of Model 2 and 3 shows higher statistics for small number subscriber numbers which indicates better utilization of the invested system capacity.

## 5. Energy Efficient Operation

Energy efficiency is evaluated in two operation modes as described in [11]. For the first methodology, the proposed system can be utilized by considering the increase in take up rates.

Minimal number of DFB sources and optical amplifiers would be activated (partially operated system) at different stages of the network growth in order to minimize the power consumption. For the second methodology, the network can be utilized for fully operated mode. In this case, traffic demand adaptive power management could be applied to reduce power consumption. This could ensure the use of system components according to demand from active end users.

### 5.1. Power reduction while considering take up rates

All the network components, both in CO and DP, have to be activated without considering active subscribers for the conventional system (Model 1). Therefore, power consumption cannot be achieved by utilizing the take up rates. On the other hand, for Model 2 and 3, only some of the DFB sources and optical amplifiers need to be activated with respect to active end users. This would lead to achieve significant decrease for investment costs at the initial deployment with more power efficient system. Table I shows the key power consumption data that we use in the study.

Table I. Key power consumption data for system components.

Component	Power consumption in Watts	Reference Model
DFB laser source	1.2	[5]
SOA switch	0.1	[34]
AWG	5	[11]
PIN photodiode	1	[5]
MZ-MOD	0.051	[35]
EDFA	25	[11]
MEMS	1.5	DICON 1 x N MEMS Switch

Power consumption per user is calculated by using equation (1) as shown below [10].

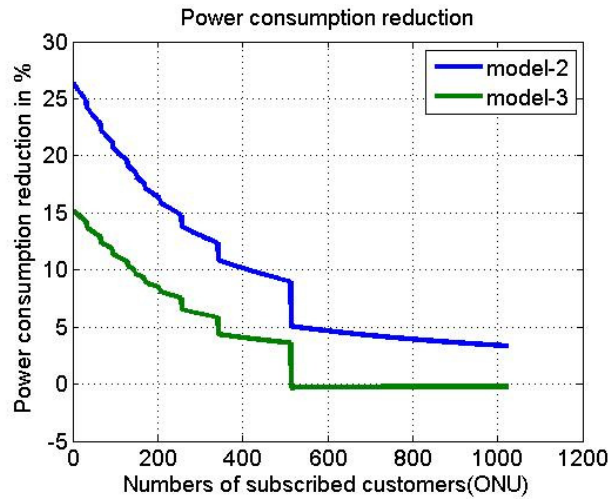
$$P_{user} = \frac{2 \cdot P_{CO}}{N} + \frac{32 \cdot P_{DP}}{N} + P_{CPE} \quad (1a)$$

$$P_{user} = 2 \cdot \left( \frac{P_{CO}}{N} + \frac{16P_{DP}}{N} \right) + P_{CPE} \quad (1b)$$

$$P_{user} = 2 \cdot \left( \frac{P_{CO}}{N} + \frac{P_{DPs}}{N} \right) + P_{CPE} \quad (1c)$$

where  $P_{CPE}$ ,  $P_{DP}$  and  $P_{CO}$  are powers consumed by a customer premises equipment, a DP, and a terminal unit at the CO, respectively.  $N$  is the number of subscribed customers which are sharing CO and DPs as well. The factor of two is to account for additional overheads such as external power supplies and cooling requirements at the CO. New subscriber can connect to the network from any of the 32 DPs and may not distributed equally among the DPs. Therefore, all the power in DPs are considered in total and averaged instead of taking a single DP for simulation as can be seen from equation (1a-1c).

Power consumption reduction for model-2 and model-3 in relative to model-1 is shown in Fig. 7.



**Figure 7** Power consumption characteristics for Models 2 and 3 as compared to Model 1

The performance in power consumption reduction for Model 2 is greater than Model 3 due to the number of active SOA switches used at the input of 32x32 AWG. The power consumption of an SOA switch is almost independent of optical signal. Switching speed of an SOA switch reconfiguration is in nanosecond timescale. In [37], authors presented a quadratic trend of the SOA consumption as a function of the input signal power. The values of power consumption are calculated and experimentally validated in [37]. At a lower bit rate 5 Gbps, the power consumption of the optical switch (OS) equipped with bulk type SOA is lower than that of the OS equipped with multiple-quantum-well (MQW) type SOA. On the contrary, as soon as the bit rate increases, MQW type SOA consumes less power than the bulk type SOA [34, 37]. Therefore, bulk type SOA are considered in this study to analyze SOA power consumption in our proposed architecture. The proposed SOA array optical switch configuration, in Model 2, is used as one step gate to the input ports of central AWG and switches could turn on/off in cycle

depending on the active number of subscribers. A single SOA switch is used which consumes less power than MEMS switch as can be seen in Table I. When the numbers of active subscribed users are less than 512, a minimum 5% and maximum of 26% percent power is reduced by Model 2 while for Model 3 the range is between 0% and 15%.

## 5.2. Power consumption, reduction and energy efficiency in traffic adaptive mode

### 5.2.1. Subscriber profile in traffic adaptive mode

The main objective of this model is to analyze the energy efficiency of the proposed models by applying time dependent traffic model. There are similar studies, [38] and [39], in the literature for these analysis. Traffic model for hybrid fiber coax (HFC) networks are studied in [38] which shows sinusoidal fluctuation of traffic demand over a time in a day (24 hours). Similar traffic model is considered for our analysis while utilizing traffic data from active subscribers during a day (24 hours).

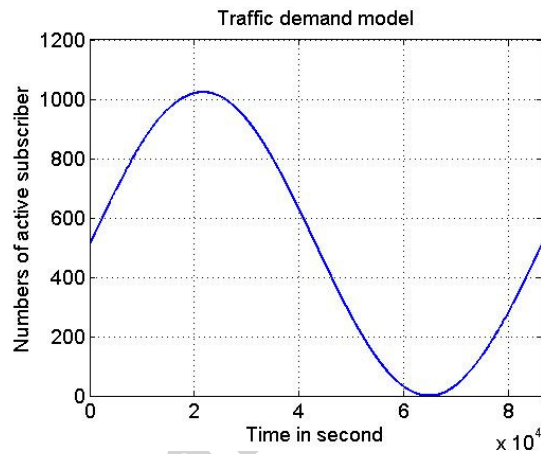
There are two assumptions that could be considered for traffic demand model. First one is to expect a higher amount of traffic as soon as the number of active subscribers increases. On the other hand, all subscribers could be active for the second assumption while the demand might vary over the time from lower bandwidth (internet browsing) to higher bandwidth (video conferencing). First assumption is considered for our proposed architecture since CRM modules could dynamically reconfigure the system characteristic based on active subscriber's traffic fluctuations. Fig. 8 depicts the model for the number of active subscribers over a periodic time, which shows a sinusoidal pattern fluctuation over a periodic time  $T$  [11].  $N(t)$  is the number of active subscribers over time  $t$ .  $N_{\max}=1024$  and  $N_{\min}=0$  are the maximum and minimal numbers of active subscribers, respectively.  $N(t)$  is expressed as (2)

$$N(t) = \frac{N_{\max} + N_{\min}}{2} + \frac{N_{\max} - N_{\min}}{2} \sin\left(\frac{2\pi t}{T}\right) \quad (2)$$

Depending on the number of active subscribers, CRM modules (both for Model 2 and 3) dynamically route the optical signals to the desired output ports of the central AWG. For this purpose, the system dynamically configures the required number of DFB sources and optical amplifiers as well. For instance, if  $N(t)$  is 10% of the total number of subscribers, there will be 105 active subscribers in the system. Therefore, the required number of DFB sources is reduced

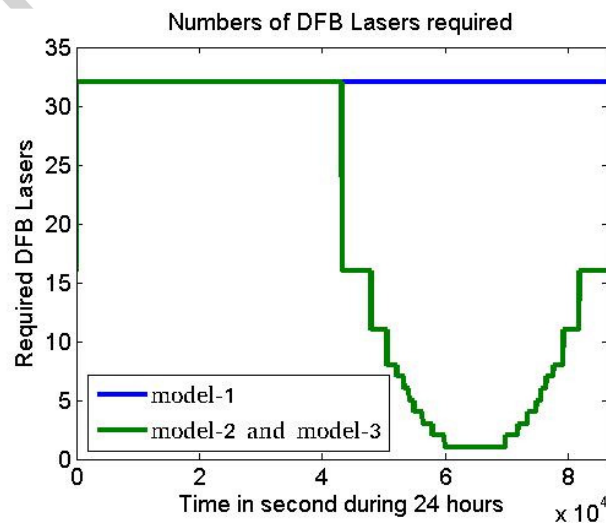


to 4. The number of DFB sources will be increased if the number active subscribers change over time. It should be noted that the switching time for DFB laser is in the range of 40 picoseconds. While considering the traffic demand model in Fig. 8, the progress of required DFB sources quantity in 24 hours period of time is illustrated in Fig. 9. For simulation analysis, time unit is defined in seconds. Therefore in Figure 8 and 9, the time axis shows maximum of  $8.64 \times 10^4$  seconds which is equal to 24 hours and the grid points  $2 \times 10^4$ ,  $4 \times 10^4$ ,  $6 \times 10^4$  and  $8 \times 10^4$  seconds represent 5.5, 11.11, 16.66 and 22.22 hours of the day respectively.



**Figure 8** Model for active subscribers in traffic adaptive mode.

The active users can be zero only for small period of time range which is just after midnight within 24 hours of the day. Therefore, the probability for active user to be zero is very small as can be seen from Figure 8.



**Figure 9** Progress of required DFB sources quantity in 24 hours period of time.

The system is configured as a fully operated operation for which all the 1024 end users are connected to the system. The subscribers can be active at the same time ( $N_{\max}$  equals to 1024) or none of them could be active ( $N_{\min}$  equals to 0). It could be stated, from Figure 9, that Model 2 and Model 3 use less than 50% of the DFB sources installed for half of the period.

### 5.2.2. Power consumption and reduction in traffic adaptive mode

Power consumption, for the proposed models, is also analyzed before and after the traffic adopting mode operation. Instantaneous power for traffic adopting mode depends on time [11] and expressed in equation (3). Instantaneous power  $P(t)$  depends on time and can be discretized in to small scale within one period (24 hours) as can be seen in equation (4). In each instant time, the consumed power depends on the number of active ONUs.  $P(i)$  is the power consumption with respect to active subscribers in time instant  $i$  which is a positive  $Z$  integer value. Finally,  $P$  is the total power consumption in one period.

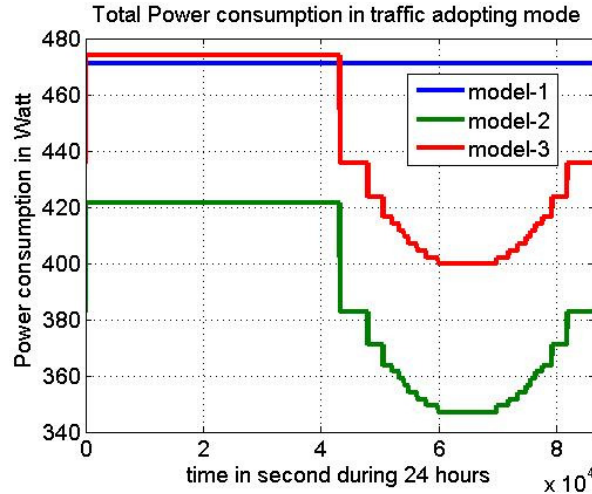
$$P(t) = 2 \cdot (P_{TU}(t) + P_{RN}(t)) \quad (3)$$

$$P(i) = 2 \cdot \left( \frac{P_{CO}(i) + P_{DPS}(i)}{N} \right) + P_{CI} \quad (4)$$

$\forall i \leq 24 * 3600$

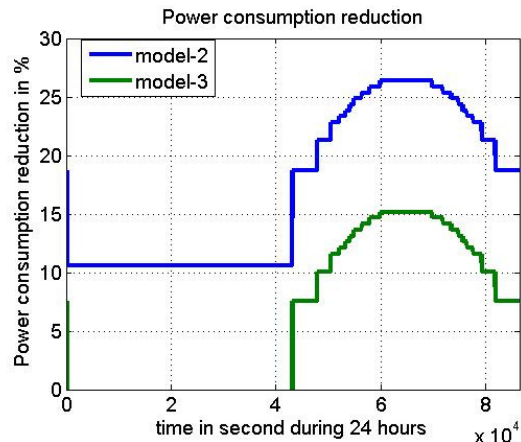
$$P = \sum_{i=1}^{24*3600} P(i) \quad (5)$$

Power consumption figures depend on the minimum and maximum number of active subscribers. Power consumption characteristics for the proposed models are illustrated in Fig. 10.



**Figure 10** Power consumption characteristics for the proposed models.

The power consumed by Model 3 is greater for the interval 1 to 4 since all the 32 DFBs are turned on which can also be seen in Figure 7. In the same period of time, Model 3 consumes also slightly more power than Model 1 due to the power usage of MEMS switch. It could be stated that the traffic-adaptive mode saves minimally up to 120W for Model 2 and 72W for Model 3 respectively in relative to Model 1. These consumption characteristics are achieved at the time of the minimum number of active subscribers among the fully operated system. Percentage power consumption of Model 2 and 3 relative to Model 1 (conventional system) is shown in Fig. 11.



**Figure 11** Percentage power consumption of Model 2 and 3 relative to Model 1.

It can be seen that 26% and 15% power consumption is reduced by using array of SOA switches and MEMS for Model 2 and Model 3 respectively at minimum traffic time of the day. On the

other hand, in the case of maximum traffic condition, 10% power consumption reduction is achieved Model 2 and no power consumption reduction is achieved for Model 3.

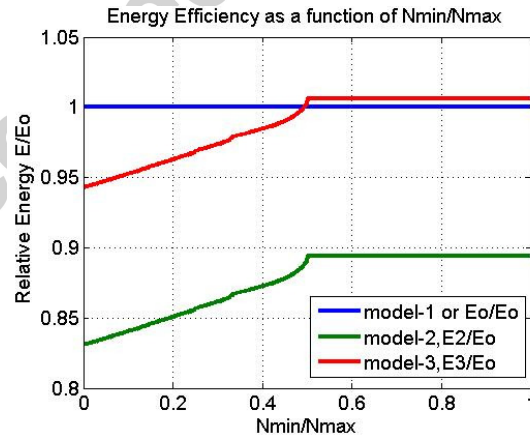
### 5.2.3. Energy efficiency in traffic adopting mode

Power consumption figures rely on the  $N_{max}$  and  $N_{min}$  characteristics of the proposed systems. On the other hand, it is crucial to observe the energy efficiency on various ratios of  $N_{max}/N_{min}$ .

Energy is defined as the sum of all power consumption in each time instant for a period of time or can be described as an integral of power over the period of time. To understand the energy savings of the proposed systems, energy reduction parameter is used as  $\varepsilon=E/E_0$  [11] where  $E$  and  $E_0$  can be expressed as (4)

$$E = \int_0^T P(t)dt \text{ and } E_0 = \int_0^T P_0(t)dt \quad (4)$$

$E_0$  is the energy consumption for constant power as in Model 1 where no energy is saved for any ratio of  $N_{max}$  and  $N_{min}$ . In addition,  $E$  is energy consumption ( $E_2$  for Model 2) and ( $E_3$  for Model 3) with dynamic range of  $N_{max}$  and  $N_{min}$ . Fig. 12 depicts the energy efficiency for the proposed models as a function of  $N_{min}/N_{max}$ .



**Figure 12** Energy efficiency a function of  $N_{min}/N_{max}$ .

If the number of active subscribers is high (close to  $N_{max}$ ) in 24 hours of day, Model 1 and 2 would have similar relative energy characteristics. Model 3 would have slightly bigger value due to available MEMS switch in the proposed architecture. It can also be seen from Fig. 12 that for

$N_{min}/N_{max}$  ratio smaller than 0.5, the minimum energy saving of 11% and maximum of 23% could be achieved by utilizing Model 2. On the other hand, maximum of 6% energy saving is achieved for Model 3.

## 6. Conclusion

We have presented a WDM/TDM PON based FTTH network architecture featuring the dynamic and reconfigurable transmission of next generation OFDM based wireless technologies. In addition to a conventional network (Model 1) design, two different CRMs are proposed through paper. For Model 2, dynamic allocation can be achieved by controlling the array of SOA switches at the CO with active provision. On the other hand, MEMS switching fabric is used in the CO to utilize dynamic assignment for Model 3. It could be stated from the results that as soon as the number of subscribers is less than 512, effective take-up rates are high for Model 2 and 3. This means that the systems with CRMs have much better utilization of the system resources compared to the Model 1 which require fewer OLTs and amplifiers are to be installed with power efficient scenarios. In addition, 26% and 10% power consumption can be achieved, for Model 2, at the minimum and maximum traffic conditions respectively. Minimum energy saving of 11% and maximum of 23% could be achieved by utilizing Model 2 when  $N_{min}/N_{max}$  ratio is smaller than 0.5. Finally, it could be stated that Model 2 is more energy efficient than both for Model 1 and Model 3 with cost efficient and power efficient characteristics.

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Editable tables for our manuscript (OSN 352) can be seen as shown below;

Table I. Key power consumption data for system components.

Component	Power consumption in Watts	Reference Model
DFB laser source	1.2	[5]
SOA switch	0.1	[34]
AWG	5	[11]
PIN photodiode	1	[5]
MZ-MOD	0.051	[35]
EDFA	25	[11]
MEMS	1.5	DICON 1 x N MEMS Switch

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Editable equations for our manuscript (OSN 352) can be seen as shown below;

$$P_{user} = \frac{2 \cdot P_{CO}}{N} + \frac{32 \cdot P_{DP}}{N} + P_{CPE} \quad (1a)$$

$$P_{user} = 2 \cdot \left( \frac{P_{CO}}{N} + \frac{16P_{DP}}{N} \right) + P_{CPE} \quad (1b)$$

$$P_{user} = 2 \cdot \left( \frac{P_{CO}}{N} + \frac{P_{DPs}}{N} \right) + P_{CPE} \quad (1c)$$

$$N(t) = \frac{N_{max} + N_{min}}{2} + \frac{N_{max} - N_{min}}{2} \cdot \sin\left(\frac{2 \cdot \pi \cdot t}{T}\right) \quad (2)$$

$$P(t) = 2 \cdot (P_{TU}(t) + P_{RN}(t)) \quad (3)$$

$$P(i) = 2 \cdot \left( \frac{P_{CO}(i) + P_{DPs}(i)}{N} \right) + P_{CI} \quad (4)$$

$\forall i \leq 24 * 3600$

$$P = \sum_{i=1}^{24*3600} P(i) \quad (5)$$

$$E = \int_0^T P(t) \cdot dt \quad \text{and} \quad E_0 = \int_0^T P_0(t) \cdot dt \quad (6)$$