Proceedings Paper:
Elgorashi, TEH, Elmirghani, JMH and Dong, X (2013) Energy efficiency of Optical OFDM-based networks. In: 2013 IEEE International Conference on Communications. ICC 2013 - 2013 IEEE International Conference on Communications, 09-13 Jun 2013, Budapest, Hungary. IEEE , 4131 - 4136.

https://doi.org/10.1109/ICC.2013.6655209

Energy Efficiency of Optical OFDM-based Networks

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***Abstract*— Orthogonal Frequency Division Multiplexing (OFDM) has been proposed as an enabling technique for elastic optical networks to support heterogeneous traffic demands. In this paper, we investigate the energy efficiency of rate and modulation adaptive optical OFDM-based networks. A mixed integer linear programming (MILP) model is developed to minimize the total power consumption of optical OFDM networks. We differentiate between two optimization schemes: power-minimized and spectrum-minimized optical OFDM-based networks. The results show that while similar power consumption savings of up to 31% are achieved by the two schemes compared to conventional IP over WDM networks, the spectrum-minimized optical OFDM is 51% more efficient in utilizing the spectrum compared to the power-minimized optical OFDM.**

I. INTRODUCTION

Following the increase in the networks size, the power consumption of network equipment, such as severs, amplifiers, routers, storage devices and communication links, has rapidly increased [1]. Given the ecological and economic impact, significant research efforts are focused on reducing the energy consumption of ICT networks. Energy-efficient and cost-effective solutions are needed to meet the increasing demand for high capacity networking infrastructures. In the last decade, wavelength division multiplexing (WDM) has emerged as the technology of choice to increase networks bandwidth. Recent technological advances in optical networks have enabled data rates per wavelength of 40 and 100 Gb/s with extended transmission distance. In our previous work, we studied different energy-efficient approaches for IP over WDM [2]-[4]. However, the rigid nature and coarse granularity of WDM networks results in inefficient capacity utilization because of the bandwidth mismatch between the application layer with bandwidth requirements varying from several to hundreds Gb/s, and the wavelength channels with data rates of 10 Gb/s and beyond. Current WDM networks address this mismatch by allowing sub-wavelength granularity connections to be groomed onto a single lightpath which results in extra cost and power consumption [5], or by allocating multiple wavelengths to a connection if the requested bandwidth is higher than that of a single wavelength, however, such an approach suffers from low spectral efficiency as adjacent wavelength must be separated by guard bands.

A promising solution to address this bandwidth mismatch is to support fine granularity through elastic spectrum allocation [6]-[8] where connection requests are allocated the minimum spectral resources required. Recently, Orthogonal Frequency-Division Multiplexing (OFDM) has been proposed as an enabling technique for elastic optical networks [9], [10]. Fig.1 compares the spectrum utilization of WDM networks and OFDM-based optical networks. Optical OFDM-based networks support a higher spectral efficiency as they can exactly provide the bandwidth needed to cater for the requirement of building a link of a certain traffic rate and consequently, the relevant network components can work at the required rate. In contrast to the conventional WDM where frequency guard bands are required between adjacent channels, OFDM improves the spectrum utilization by allowing the spectrum of adjacent subcarriers to overlap as orthogonality will ensure the separation of subcarriers at the receiver side [10].

In conventional optical networks the available capacity is limited to the worst-case optical path design to ensure quality of transmission (QoT). However, optical paths of higher optical signal-to-noise ratios (OSNR) (usually associated with lower reach) can support significantly higher capacities. Optical OFDM supports distance-adaptive spectrum allocation by adapting the modulation format according to the end-to-end physical conditions of the optical path [11], [12]. This advantage is further discussed in Section III.

A number of papers in the literature have studied the energy-efficiency of OFDM-based wireless systems, e.g. [13], [14]. However, the power savings introduced by optical OFDM-based networks is not a well investigated topic. In [15] the authors studied the energy efficiency of optical interconnects in data-centers considering the use of adaptive OFDM. In this work we investigate the energy efficiency of optical OFDM-based network. In a recently published paper [16], the authors studied the energy efficiency of backbone networks with optical OFDM. They developed a mathematical model considering flexible bandwidth allocation. However, our work is a more detailed study. In addition to the flexible bandwidth allocation, we also consider distance-adaptive spectrum allocation where the modulation level of subcarriers is adapted according to OSNR, which is mostly associated with the transmission distance. In the model developed in [16], traffic flows are allowed to be groomed together. However, implementing grooming in the IP layer for optical OFDM-based networks is not the best approach as optical OFDM exactly allocates the bandwidth needed to cater for the requirements of a traffic demand. Therefore the model developed in this work does not support traffic grooming.

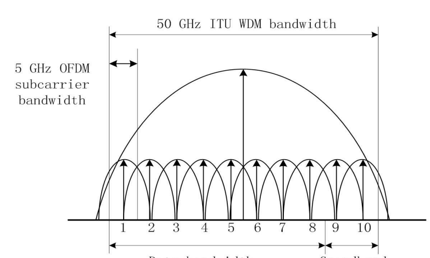

Fig.1 Spectrum utilization of WDM networks and optical OFDM-based networks

In this paper, we compare optical OFDM-based networks to conventional IP over WDM networks with different wavelength rates (10/40/100Gb/s). We also compare optical OFDM-based networks to mixed line rate (MLR) networks where wavelengths of different rates are deployed over the same fibre.

II. OFDM-BASED OPTICAL NETWORKS

Fig.2 illustrates the block diagram of a typical optical OFDM system. At the transmitter side, the serial-to-parallel (S/P) module converts the incoming high-bit-rate data stream to low-bit-rate parallel blocks of symbols. The symbols are mapped by some type of quadrature amplitude modulation (QAM) or phase-shift keying (PSK) onto orthogonal carriers with equally spaced frequencies. The time-domain OFDM symbols are obtained by inverse fast Fourier transformation (IFFT). The discrete parallel symbols go through parallel-to-serial (P/S) conversion and digital-to-analog conversion (DAC) to generate a continuous time domain signal. In the optical transmitter module (OTM), electrical OFDM signals are modulated over an optical carrier using a directly modulated laser (DML) or an externally modulated laser (EML) [17].

At the optical receiver module (ORM), the optical OFDM signal is detected using either direct detection (DD) or coherent detection (CO-D) [10], [12], [17]. To recover data from the orthogonal subcarriers, the serial signal is converted to parallel data blocks and the OFDM signal is converted back to the frequency domain using forward FFT. At the receiver side, the information symbols are affected by signal phase and amplitude level shifting caused by chromatic dispersion of the optical channel. Therefore, equalization is needed after the forward FFT to obtain an OFDM signal without forward error [10], [17]. After equalization, each subcarrier is demodulated and data is converted to serial.

III. MODULATION LEVEL AND QOT OF OPTICAL OFDM-BASED NETWORKS

As mentioned in Section I, OFDM supports distance-adaptive spectrum allocation. This advantage stems from the fact that each OFDM subcarrier can be processed individually. Unlike conventional fixed hardware implementations, in OFDM the signal properties can be easily changed by software as digital signal processing is implemented at both the receiver and the transmitter ends. Therefore, the modulation format can be adapted according to the end-to-end physical condition of the optical path [11]. In terms of OSNR, which is mostly associated with distance, we can add an extra bit per symbol for every 3 dB gain in OSNR. Therefore we can make use of the flexibility offered by OFDM to adapt the modulation level of subcarriers to increase the available capacity. The link capacity (C) is given as a function of the link length [11]:

$$C = \frac{C_0}{2}\left(1 + \log_2 \frac{2 \cdot l_0}{l}\right) \quad l \leq 2 \cdot l_0 \quad (1)$$

where l_0 is the maximum distance, C_0 is the capacity associated with the worst-case optical path (path with the maximum distance) and l is the link length. Note that the OSNR improves by 3 dB as the transmission distance decreases to half, allowing the modulation format to increase by 1 bit/symbol, e.g. 8-QAM (3 bit per symbol) can be used instead of QPSK (2 bit per symbol) or 16-QAM (4 bit per symbol) can be used instead of 8-QAM.

IV. POWER CONSUMPTION OF OFDM-BASED OPTICAL NETWORK

As discussed above, optical OFDM-based networks provide flexible bandwidth by supporting the allocation of a variable number of subcarriers and adapting the modulation level of subcarriers to increase the available capacity, resulting in significant reduction in the power consumption of the whole network. In this work, we investigate the power consumption savings introduced by OFDM-based optical network compared to WDM networks. To enable bandwidth flexible transmissions, the fixed-bandwidth components used for WDM networks need to be replaced with network components that can work at flexible rates. In this section, we study the power consumption of the different network components in an optical OFDM-based network and compare it to the power consumption of the same components in IP over WDM networks. We consider the three most power consuming components: IP port, transponder and erbium doped fibre amplifier (EDFA).

As the electronic processing of OFDM signals is implemented in the transponder, the IP over optical OFDM network can use IP router ports similar to those used in IP over WDM networks. We assume an adaptive line rate (ALR) power profile for the IP ports (although not available in routers today, it is targeted by router vendors), where the power consumption depends on the load, to calculate the power consumption of router ports supporting flexible wavelength rates.

The large gain bandwidth of EDFAs makes them useful for WDM networks as a single EFDA can simultaneously amplify many data channels at different wavelengths within its gain region [18]. Similarly EDFAs can be used in OFDM-based optical networks.

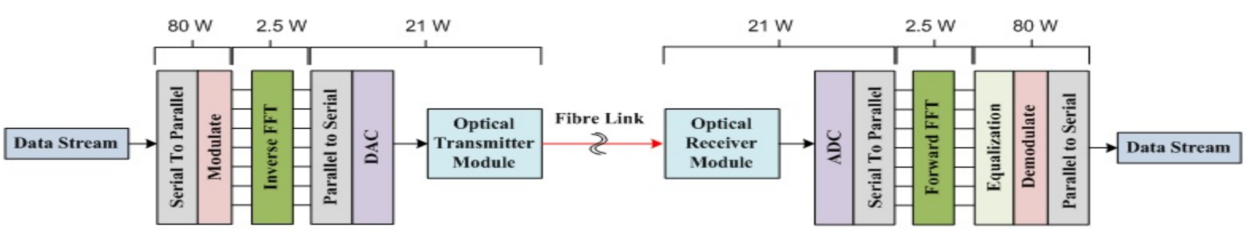

Fig. 2 Block diagram of a typical optical OFDM communication system

In addition to the ability to allocate a variable number of subcarriers and modulate each subcarrier individually, OFDM transponders need to perform IFFT and FFT processes. The power consumption of the OFDM transponder mainly depends on the electronic processing, modulation level and the number of subcarriers. The highest power consumption of the OFDM transponder occurs when an optical OFDM signal uses the maximum number of subcarriers with the highest modulation level. We assume OFDM transponders to have an ALR power profile [19].

V. MILP MODEL FOR OPTICAL OFDM-BASED NETWORKS

In this section we develop a MILP model to minimize the power consumption of the IP over optical OFDM networks. The MILP model is based on the following scenario:

- Traffic demands utilize a continuous spectrum, i.e. a contiguous set of subcarriers (spectrum continuity constraint) [12]. To maintain the spectrum continuity constraint, the traffic between a node pair is not allowed to split.
- The maximum number of subcarriers that the OFDM transponder can process is limited.
- As discussed in Section III, the maximum modulation level of the traffic demand between different node pairs depends on the OSNR which is mostly associated with transmission distance. In this model, we assume that optical OFDM-based networks support three modulation levels: BPSK, QPSK and 8QAM. To achieve the maximum spectrum efficiency, OFDM transponders modulate the subcarriers of a traffic demand using the highest modulation level allowed.
- There is no need to do the grooming in the IP layer as the flexibility of OFDM can provide each traffic demand with the exact data rate needed.

Before introducing the model, the following parameters are defined:

λ^{sdt}	The traffic demand between node pair (*s, d*) at time *t*
EA_{mn}	The number of EDFAs on physical link (*m, n*) Typically $EA_{mn} = \lfloor L_{mn}/S - 1 \rfloor + 2$, where S is the distance between two neighbouring EDFAs [20]
C_r	The capacity of a single subcarrier used *r* modulation level
Np_i	The neighbouring nodes set of node *i*
PR	Power consumption of an IP router port per 1 Gb/s
PE	Power consumption of an EDFA
B	The maximum number of wavelengths on an optical fibre
NSC	The maximum number of subcarriers supported by an OFDM-transponder
LR_{max}	The maximum line rate LR_{max}
PT_{max}	The maximum power consumption of transponders working at the maximum line rate LR_{max}
R	The set of modulation levels for the subcarrier

The following variables are also defined:

ns_r^{sdt}	The number of OFDM subcarriers using modulation level *r* to serve the traffic demand (*s, d*) at time *t*
NS_{mnr}^{sdt}	The number of OFDM transponders using modulation level *r* to serve demand (*s, d*) that traverses physical link *(m, n)* at time *t*
ω_{mnt}^{sd}	$\omega_{mnt}^{sd}=1$ if the OFDM subcarriers of traffic demand (*s, d*) traverse physical link (*m, n*) at time *t*, otherwise $\omega_{mnt}^{sd}=0$
NF^{mnt}	The number of fibres on physical link (*m,n*) at time *t*

The total network power consumption is composed of:

1) The power consumption of router ports:

$$\sum_{s\in N}\sum_{d\in N: s\neq d} \lambda^{sdt} \cdot PR$$

2) The power consumption of EDFAs:

$$\sum_{m\in N}\sum_{n\in Np_m} NF^{mnt} \cdot EA_{mn} \cdot PE$$

3) The power consumption of OFDM transponders:

$$\sum_{s\in N}\sum_{d\in N: s\neq d}\left(\sum_{m\in N}\sum_{n\in Np_m}\omega_{mnt}^{sd} \cdot \left(ALR\left(\frac{\sum_{r\in R} NS_{mnr}^{sdt}\cdot C_r}{LR_{\max}}\right)\cdot PT_{\max}\right)\right)$$

where *ALR*() is the ALR energy profile function.

For example, a traffic demand of 100 Gb/s with BPSK modulation will require 2 OFDM transponders working at the maximum line rate (40Gb/s) and 1 transponder working at 20Gb/s. As discussed in Section III, the maximum line rate the OFDM transponder can support depends on the distance between the source and destination node pair.

The model is defined as follows:

Objective: Minimize

$$\sum_{t\in T}\left(\sum_{s\in N}\sum_{d\in N: s\neq d}\lambda^{sdt}\cdot PR + \sum_{s\in N}\sum_{d\in N: s\neq d}\left(\sum_{m\in N}\sum_{n\in Np_m}\omega_{mnt}^{sd}\cdot\left(ALR\left(\frac{\sum_{r\in R} NS_{mnr}^{sdt}\cdot C_r}{LR_{\max}}\right)\cdot PT_{\max}\right)\right) + \sum_{m\in N}\sum_{n\in Np_m} NF^{mnt}\cdot EA_{mn}\cdot PE\right) \quad (2)$$

Subject to:

$$\sum_{n\in Np_m}\omega_{mnt}^{sd} - \sum_{n\in Np_m}\omega_{nmt}^{sd} = \begin{cases} 1 & m = s \\ -1 & m = d \\ 0 & otherwise \end{cases} \quad (3)$$

$$\forall\, s, d, m\in N: s \neq d, t\in T$$

$$\lambda^{sdt} \leq \sum_{r \in R} ns_r^{sdt} \cdot C_r$$
$$\forall\ s, d \epsilon N: s \neq d, t \epsilon T \text{ (Power-minimized)}$$
$$\lambda^{sdt} \leq \sum_{r \in Rmax} ns_r^{sdt} \cdot C_r \quad (4)$$
$$\forall\ s, d \epsilon N: s \neq d, t \epsilon T \text{ (Spectrum-minimized)}$$

$$\sum_{n \epsilon Np_m} NS_{mnr}^{sdt} - \sum_{n \epsilon Np_m} NS_{nmr}^{sdt} = \begin{cases} ns_r^{sdt} & m = s \\ -ns_r^{sdt} & m = d \\ 0 & otherwise \end{cases} \quad (5)$$
$$\forall\ s, d, m \epsilon N: s \neq d, r \in R, t \epsilon T$$

$$NS_{nmr}^{sdt} \geq 0 \quad (6)$$
$$\forall\ s, d, m \epsilon N, n \epsilon Np_m: s \neq d, r \in R, t \epsilon T$$

$$NS_{nmr}^{sdt} \leq \omega_{nmt}^{sd} \cdot NMAX \quad (7)$$
$$\forall\ s, d, m \epsilon N, n \epsilon Np_m: s \neq d, r \in R, t \epsilon T$$

$$NF^{mnt} \cdot B \geq \sum_{s \epsilon N} \sum_{d \epsilon N: s \neq d} \left(\sum_{r \epsilon R} NS_{nmr}^{sdt} / NSC\right) \quad (8)$$
$$\forall\ t \epsilon T, m \epsilon N, n \epsilon Np_m$$

Constraint (3) gives the flow conversion in the optical layer and ensures that traffic demands are not allowed to split.

Constraint (4) ensures that the capacity of the subcarriers allocated to a traffic demand is large enough to support the traffic demand. In this constraint, we differentiate between two optimization problems: power-minimized and spectrum-minimized optical OFDM-based networks. In power-minimized optical OFDM-based networks, the MILP model will select the modulation format that minimizes the power consumption of the network. However, this will lead the model to choose the lowest possible modulation format to fit the traffic demand with best granularity. In spectrum-minimized optical OFDM-based networks, the highest modulation format possible will always be used, and then the total bandwidth of the subcarriers is minimized.

Constraint (5) ensures that for each traffic demand, the number of OFDM subcarriers using modulation level r entering node m is equal to the number of the subcarriers using modulation level r leaving node m. This is to conserve the number of OFDM subcarriers using modulation level r.

Constraints (6) and (7) guarantee that the value of the variable NS_{nmr}^{sdt} is related to the value of the binary variable, where NMAX is a large enough number. Constraint (8) ensures that the number of OFDM wavelengths allocated to a traffic demand does not exceed the number of wavelength in an optical fibre.

VI. RESULTS AND ANALYSIS

We considered the NSFNET network, depicted in Fig.4, to evaluate the power consumption of the optical OFDM-based network. The NSFNET network consists of 14 nodes and 21 bidirectional links. As NSFNET covers the US, different parts of the network fall in different time zones, i.e. nodes experience different traffic demands at any given point in time. The US is covered by four time zones: Eastern Standard Time (EST), Central Standard Time (CST), Mountain Standard Time (MST) and Pacific Standard Time (PST). There is an hour time difference between each time zone and the next, we use EST as the reference time. Note that time zones dictate habits and therefore network utilization and traffic demands in our case.

Fig.3 shows the average traffic demands in different time zones [21]. The average traffic demand between each node pair ranges from 20 Gb/s to 120 Gb/s (the average is 80 Gb/s) and the peak occurs at 22:00. We assume that the traffic demand between each node pair in the same time zone is random with a uniform distribution and no lower than 10 Gb/s. In the following results, the network power consumption is given versus the hourly variations of network traffic.

We compare the power consumption of optical OFDM-based networks to conventional WDM networks. We consider both systems with a channel bandwidth of 50GHz (as in Fig.1). The maximum number of subcarriers for each OFDM channel is 10, each of 5GHz. Two of the channels are used as guard bands. We consider 8QAM as the highest modulation level for optical OFDM, therefore, the maximum line rate for an OFDM transponder LR_{max} is: 5(GHz)×3 (Bit/Hz) ×8=120 Gb/s. For the WDM network, we consider three different wavelength capacities: 10Gb/s, 40Gb/s and100Gb/s and assume BPSK as the modulation level associated with the maximum transmission distance l in the NSFNET network between node 1 and node 14.

For the optical OFDM-based network the maximum capacity of each subcarrier for different transmission distance C_r can be calculated from equation (1) considering C_o as the capacity of BPSK. Note that C_r can only be the capacity associated with BPSK, QPSK and 8QAM, and the C calculated from Equation (1) gives the upper bound.

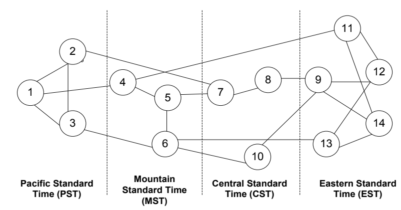

Fig.3. The NSFNET network with time zones

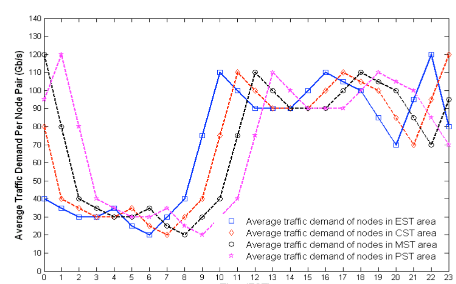

Fig.4. Average traffic demand in different time zones

Table I shows the network parameters in terms of number of wavelengths, wavelength rate, distance between two neighbouring EDFAs, and power consumption of different components in the WDM network. The IP router port power consumption is derived from Cisco's 8-slot CRS-1 data sheets [22]. Note that the power consumption of the IP router port takes into account the power consumption of the different shared and dedicated modules in the IP router. The 8 slot CRS-1 consumes about 8kW and therefore the power consumption of each port is given as 1kW [20], [22]. Based on the power consumption of the 40Gb/s IP port, we can calculate the power consumption per 1Gb/s of an IP router port (*PR*) as 25 W/Gb/s. The power consumption of the 10Gb/s and 40Gb/s WDM transponders is derived from Cisco ONS 15454 10-Gbps Multirate Transponder Card [23] and Cisco ONS 15454 40-Gbps multi-rate transponder card [24], respectively. The power consumption of the 100Gb/s WDM transponder is calculated based on the ratio between the power consumption of the 40Gb/s WDM transponder and the 100Gb/s WDM transponder given in [25]. The power consumption of the EDFAs is derived from Cisco ONS 15501 EDFA [26].

We calculate the power consumption of an OFDM transponder working at the maximum rate of 120 Gb/s based on the block diagram shown in Fig.2. A DSP module performs serial to parallel (S/P) conversion and modulation at the transmitter side and another DSP module performs equalization, demodulation and P/S conversion at the receiver side. As shown in Fig.2, the power consumption of the DSP module is estimated as 80W [27]. In addition, state-of-the-art parallel optical interconnects were shown to operate with less than 5 mW/Gb/s total power consumption [28]. The power consumption of the IFFT and FFT modules is estimated as 0.4 mW/Gb/s [29]. The power consumption of the P/S, DAC and the optical transmitter module is estimated as 21W [30]. Also the power consumption of the optical receiver module and the analogue to digital converter (ADC) and S/P is estimated as 21W. We estimate the power consumption of OFDM transponders working at lower rates by assuming a linear power consumption profile [19].

TABLE I
INPUT DATA FOR THE SIMULATION

Distance between two neighbouring EDFAs	80 (km)
Capacity of each wavelength	40 (Gb/s)
Power consumption of a WDM router port (40Gb/s)	1000 (W)
Power consumption of a WDM transponder (10Gb/s)	45 (W)
Power consumption of a WDM transponder (40Gb/s)	73 (W)
Power consumption of a WDM transponder (100Gb/s)	135 (W)
Power consumption of an EDFA	8 (W)

To emphasis the power savings achieved by the optical OFDM-based network, Fig.6(a) shows the power consumption of the optical layer under the bypass approach considering the traffic profile in Fig. 3. The optical OFDM-based network saves 55%, 29% and 48% of the optical layer power consumption compared to WDM networks deploying wavelength capacities of 10Gb/s, 40Gb/s, 100Gb/s, respectively. In the optical layer, the maximum saving is achieved compared to the WDM network with the 10G/s wavelength rate as the power consumption of WDM transponders does not increase linearly with the wavelength rate (see Table I). Therefore deploying a 10Gb/s wavelengths to support a traffic demand with an average of 80Gb/s is less energy-efficient than deploying wavelengths of 40Gb/s and 100Gb/s. However this is not the case for router ports in the IP layer as discussed below.

As a result of the higher efficiency of MLR networks compared to WDM networks deploying a single wavelength rate, the power savings achieved by the optical OFDM-based network compared to MLR networks is limited to 7%.

Fig.6(a) also shows that the difference in power consumption of the optical layer between the power-minimized and spectrum-minimized optical OFDM-based networks is limited to 2%.

Fig.6(b) shows the total network power consumption under the bypass approach. The power minimized optical OFDM-based network saves 10%, 14% and 31% of the total network power consumption compared to WDM networks deploying wavelength capacities of 10Gb/s, 40Gb/s and 100Gb/s, respectively. The maximum saving is achieved compared to the IP over WDM network with the 100Gb/s wavelength rate. This is because the lower wavelength granularity results in lower utilization of the IP router ports and transponders and consequently lower power consumption as the power consumption of IP router ports (the most energy consuming devices in the network) increases linearly as the capacity increases. The power savings achieved by the optical OFDM-based network compared to MLR networks is limited to 7%. Similar power savings are achieved by the spectrum-minimized OFDM scheme.

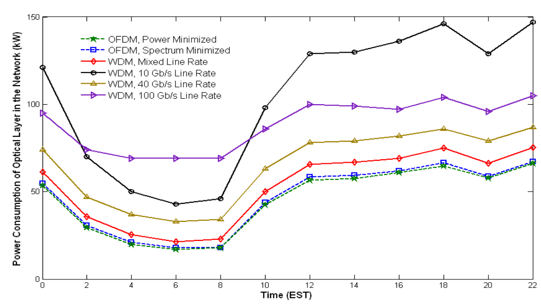

Fig.5(a). The optical layer power consumption considering optical OFDM and conventional WDM under the bypass approach

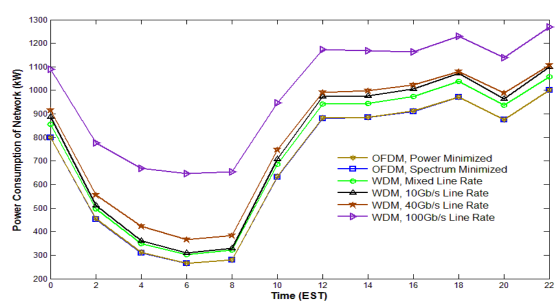

Fig.5(b). Network total power consumption considering optical OFDM and conventional WDM networks under the bypass approach

In Fig.6, we investigate the spectral efficiency of optical OFDM-based networks. The spectrum-minimized optical OFDM is 51% more efficient in utilizing the spectrum compared to the power-minimized optical OFDM while similar power consumption savings are achieved by the two schemes.

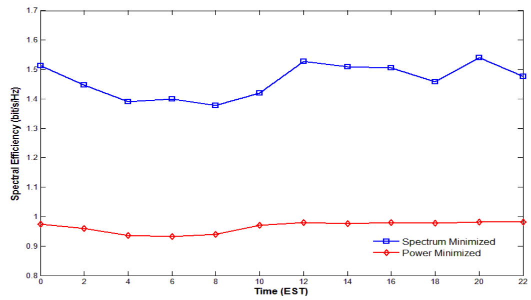

Fig.6. Spectral efficiency of optical OFDM-based networks

VII. CONCLUSIONS

In this paper, we have developed a MILP model to minimize the total power consumption of optical OFDM-based networks. In addition to the flexible spectrum allocation, we have also considered distance-adaptive spectrum allocation. Considering a linear profile to estimate the OFDM transponder power consumption, the results show that the optical OFDM-based network has saved 10%, 14% and 31% of the network power consumption compared to a conventional IP over WDM network with 10Gb/s, 40Gb/s and 100Gb/s wavelength rate, respectively. Compared to MLR networks, the optical OFDM-based network power saving is limited to 7%. The results also show that the spectrum-minimized optical OFDM-based network is 51% more efficient than the power-minimized network while similar power consumption savings are achieved by the two schemes.

ACKNOWLEDGMENT

The authors would like to thank the EPSRC for funding this work. They also would like to thank their collaborators at the University of Cambridge, Cambridge, U.K., for useful discussions.

REFERENCES

[1] B.G. Bathula, D. Satyanarayana and J.M.H. Elmirghani, “Energy Efficient Optical Burst Switched (OBS) Networks,” *IEEE GLOBECOM’09 workshops, 2009*, pp.1-6, 2009.

[2] Xiaowen Dong, Taisir El-Gorashi and Jaafar M. H. Elmirghani “IP Over WDM Networks Employing Renewable Energy Sources,” *IEEE/OSA Journal of Lightwave Technology,* vol. 29, No. 1, pp. 3-14, 2011.

[3] X. Dong, T. El-Gorashi, J.M.H Elmirghani, “Green IP Over WDM Networks With Data Centers”, *IEEE/OSA Journal of Lightwave Technology* vol. 29 , Issue: 12, pp. 1861 – 1880.

[4] X. Dong, T. El-Gorashi, J.M.H Elmirghani, “On the Energy Efficiency of Physical Topology Design for IP over WDM Networks,” *IEEE/OSA Journal of Lightwave Technology* vol. 30, Issue 5, 2012.

[5] M. Jinno et al., “Spectrum-Efficient and Scalable Elastic Optical Path Network: Architecture, Benefits, and Enabling Technologies,” IEEE Commun. Mag., vol. 47, issue 11, 2009, pp. 66–73.

[6] O. Gerstel, “Flexible Use of Spectrum and Photonic Grooming,” *IPR/PS ’10*, PMD3, 2010.

[7] T. Takagi *et al.*, “Algorithms for Maximizing Spectrum Efficiency in Elastic Optical Path Networks,” *Proc. ECOC 20’*, We.8.D.5, 2010.

[8] J. Armstrong, “OFDM: From copper and wireless to optical,” presented at the Proc. OFC/NFOEC 2008, San Diego, CA, 2008, Tutorial, OMM1.

[9] J. Armstrong, “OFDM for optical communications,” *IEEE/OSA Journal of Lightwave Technology,* vol. 27, no. 3, pp. 189–204, Feb. 2009.

[10] H. Rohling, T. May, K. Bruninghaus, and R. Grunheid, “Broadband OFDM radio transmission for multimedia applications,” Proc. IEEE, vol. 87, no. 10, pp.1778-1789, 1999.

[11] A. Bocoi, M. Schuster, F. Rambach, M. Kiese, C. Bunge, and B. Spinnler, “Reach-dependent capacity in optical networks enabled by OFDM,” Proc. OFC, 2009, Paper OMQ4.

[12] K. Christodoulopoulos, I. Tomkos, and E. Varvarigos, “Elastic Bandwidth Allocation in Flexible OFDM-Based Optical Networks,” *IEEE/OSA Journal of Lightwave Technology*, vol. 29, NO. 9, 2011, pp. 1354-1366.

[13] N. Papandreou and T. Antonakopoulos, “Bit and power allocation in constrained multicarrier systems: the single-user case," EURASIP J. Advances Signal Process., no. 1, vol. 2008.

[14] G. Bansal, M. J. Hossain, and V. K. Bhargava, “Adaptive power loading for OFDM-based cognitive radio systems," in Proc. IEEE International Commun. Conf. (ICC’07), pp. 5137-5142, June 2007

[15] C. Kachris, E. Giacoumidis, and I. Tomkos, “Energy-efficiency Study of Optical OFDM in Data Centers,” *Proc., OFC*, 2011.

[16] Avishek Nag, Ting Wang, and Biswanath Mukherjee, “On Spectrum-Efficient Green Optical Backbone Networks,” *IEEE GLOBECOM’11*.

[17] Y. Benlachtar, *et. al*, “Generation of optical OFDM signals using 21.4 GS/s real time digital signal processing,” *OPTICS EXPRESS*, vol. 17, no. 20, pp. 17568-17668, Sep. 2009.

[18] F. Mahad and A. Supaat, “EDFA gain optimization for WDM system,” Journal of Electrical Engineering, vol. 11, no. 1, pp. 34-37, 2009.

[19] J. Camilo C. Restrepo, C. Gruber, C. M. Machuca, “Energy Profile Aware Routing” *First International Workshop on Green Communications IEEE International Conference on Communications (ICC),* pp. 1-5, June 2009, Dresden, Germany.

[20] G. Shen and R. S. Tucker, “Energy-Minimized Design for IP over WDM Networks,” *Optical Communication and Networking*, vol.1, pp. 176-186, 2009.

[21] Y. Chen and C. Chou, “Traffic Modeling of A Sub-network by using ARIMA,” *Info-tech and Info-net, Proceedings, ICII-2001.* vol. 2, pp. 730-735, 2001.

[22] Cisco CRS-1 specification data sheet.

[23] Cisco ONS 15454 10-Gbps Multirate Transponder Card.

[24] Cisco ONS 15454 40-Gbps Multirate Transponder Card.

[25] Pulak Chowdhury, Massimo Tornatore, and Biswanath Mukherjee, “On the Energy Efficiency of Mixed-Line-Rate Networks,” *OFC 2010.* 2010.

[26] Data sheet of Cisco ONS 15501 EDFA.

[27] J. Anderson et al., “Optical Transceivers for 100 Gigabit Ethernet and Its Transport,” *IEEE Communication. Magazine,* Mar. 2010, pp. 35–40.

[28] L. Schares, et al., "Terabus: Terabit/second-class card-level optical interconnect technologies," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, pp. 1032-1044, 2006.

[29] M. Glick, Y. Benlachtar, Y and R. Killey,”Performance and Power Consumption of Digital Signal Processing Based Transceivers for Optical Interconnect Applications,” *ICTON2009,* pp. 1072 – 1075, 2009.

[30] K. Poulton, R. Neff, B. Setterberg, et al., “A 20GS/s 8b ADC with a 1MB Memory in. 0.18um CMOS”, ISSCC Dig. Tech. Paper, Feb, 2003.